

Proceedings of the
2016 Summer Topical Meeting
on
Dimensional Accuracy and Surface Finish
in Additive Manufacturing

June 27-30, 2016

Marriott Raleigh City Center
Raleigh, North Carolina, USA

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

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ASPE -- The American Society for Precision Engineering
301 Glenwood Avenue, Suite 205, Raleigh, NC 27603
P.O. Box 10826, Raleigh, NC 27605
Telephone: (919) 839-8444 Fax (919) 839-8039
Website: aspe.net

Preface

This book comprises the proceedings of the ASPE/euspen Topical Meeting on **Dimensional Accuracy and Surface Finish in Additive Manufacturing**. The contributions reflect the authors' opinions and are published as presented to ASPE without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, euspen or its editorial staff.

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Foreword

Welcome to the joint 2016 Summer Topical Meeting between ASPE and euspen on **Dimensional Accuracy and Surface Finish in Additive Manufacturing**. This year's meeting is in Raleigh, North Carolina at the Marriott Raleigh City Center. The Marriott Raleigh City Center is located in the heart of downtown Raleigh within easy access to restaurants, brew-pubs, visual and performing art venues, museums, boutiques, parks and city and state government, while North Carolina State University is just minutes away.

Meeting Co-Chairpersons:

John S. Taylor,

Lawrence Livermore National Laboratory and University of North Carolina at Charlotte

Shawn P. Moylan

National Institute of Standards and Technology

Ola L.A. Harrysson

North Carolina State University

Richard K. Leach

University of Nottingham, United Kingdom

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Program & Schedule at a Glance

Marriott Raleigh City Center

500 Fayetteville Street

Raleigh, NC 27601

(919) 833-1120

Date	Time Begin	Time End	Event	Location
Mon June 27				
	07:00		Check-in Begins	University Foyer
	07:00	08:00	Continental Breakfast	University Ballroom
	08:00	12:00	Tutorial 1 – Bate	University Ballroom
	12:00	01:30	Lunch on-your-own	Restaurant Guide
	01:30	05:30	Tutorial 3 – Kuhn	Alumni Room
	01:30	05:30	Tutorial 4 – Brown	University Ballroom
	06:00	07:00	Welcome Reception	University Foyer
	07:00	08:00	Keynote Address	University Ballroom
Tue June 28				
		07:30	Check-in Begins	University Foyer
	07:30	09:00	Continental Breakfast	University Ballroom
	08:45	12:25	Welcome & Technical Sessions	University Ballroom
	12:25	01:55	Lunch on-your-own	Restaurant Guide
	01:55	03:25	Commercial Announcements & Short Notes	University Ballroom
	03:40	05:10	Poster Session	University Foyer
	06:30	09:00	Networking Dinner	City Club Raleigh
				Dress Code Business Casual 150 Fayetteville St.-28th Floor
Wed June 29				
	07:30		Check-in Begins	University Foyer
	07:30	08:30	Continental Breakfast	University Ballroom
	08:30	11:55	Technical Sessions	University Ballroom
	11:55	01:25	Lunch on-your-own	Restaurant Guide
	01:25	05:15	Technical Sessions	University Ballroom
			Free Evening	
Thurs June 30				
	07:30		Check-in Begins	University Foyer
	07:30	08:30	Continental Breakfast	University Ballroom
	08:30	11:55	Technical Sessions	University Ballroom
	11:55	01:25	Lunch on-your-own	Restaurant Guide
	01:25	05:15	Technical Sessions	University Ballroom
	06:30	08:00	Closing Reception	Clouds Brewing Co. 126 N West Street

Conference Program in Detail

Monday, June 27, 2016

Tutorials

08:00 AM - 05:30 PM

University Ballroom and Alumni Room



Getting the Best from X-ray CT and CT Metrology with AM Parts

David J. Bate, Nikon Metrology

8:00 AM - 12:00 Noon, University Ballroom

This tutorial will cover information about X-ray CT from the basics of how the X-ray microscope generates the X-ray beam, through the process of collecting the data about the sample for the CT process and finally how that data is used to reconstruct a volume and the data is analyzed. At each part of the process the problems encountered will be discussed and methods to minimize these errors will be

suggested. The topics covered will be:

- X-ray generation – from electron beam to X-ray beam
- Mounting the sample and how to minimize the errors
- Collecting data – how to make the data good enough
- Reconstruction – typical methods and their advantages
- Finding the surface and analyzing the data
- Through this structure the following error sources will be considered
- Polychromatic beams and beam hardening
- Non point beams and convolution
- Is the manipulator accurate enough
- Thermal effects
- Cone beam artifacts
- Scattering and how to minimize it
- Statistics of the data acquisition



Design for Additive Manufacturing and the Value Proposition

Howard A. Kuhn, University of Pittsburgh

1:30 PM - 5:30 PM, Alumni Room

Counter to the hype, complexity is NOT free. Furthermore, removal of support structures as required in many of the AM processes, heat treatment, and surface finishing for critical areas add to the post-processing burden. Nevertheless, integrating material, process, and geometry considerations along with life-cycle cost models leads to a design framework by which successful applications can be

developed. This tutorial will quickly review some fundamental characteristics of the various AM processes to set the stage for a rational design approach to material and process selection, specification of feature details, avoidance of defects, part integration and cost estimation. Topological and shape optimization approaches will illustrate methods for weight reduction in mechanical and thermal load bearing applications. Finally, the potential for combining additive and subtractive manufacturing for some applications will be considered.



Principles of Surface Metrology and Multi-scale Analysis to Support Product and Process Design

Christopher A. Brown, Worcester Polytechnic Institute

1:30 PM - 5:30 PM, University Ballroom

This tutorial can be for those who are new to surface metrology and for engineers and scientists who would like a fresh look at the measurement and analysis of surface roughness. Principles and systematic categorizations for surface metrology are proposed. The emphasis is on adding value by supporting product and process

design and quality assurance with special attention to additive manufacturing. Attendees will learn how to apply multi-scale geometric analyses to discover:

- correlations between resulting roughness and manufacturing processes,
- correlations between surface performance and the roughness,
- how to discriminate surfaces, which were processed or perform differently

Welcome Reception

06:00 PM - 07:00 PM

University Foyer

The Meeting officially opens with the Welcome Reception in the University Foyer, just outside of the University Ballroom. Join us for drinks and appetizers, and network with colleagues, catch-up with long-time friends and meet new ones.

Keynote Program

07:00 PM - 08:00 PM

University Ballroom

A series of short talks will summarize the work being carried out in the United Kingdom to develop a strategy in metrology for Additive Manufacturing and will present the significant research work in metrology for Additive Manufacturing being carried out at the University of Nottingham.

- **Professor Richard K. Leach**, University of Nottingham
An Introduction to the UK Strategy in Metrology for Additive Manufacturing
- **Professor Richard K. Leach**, University of Nottingham
Research in Metrology for Additive Manufacturing in Nottingham – A New Paradigm?
- **Dr. Petros Stavroulakis**, University of Nottingham
Form Measurement for Additive Manufacturing
- **Professor Nicola Senin**, University of Perugia
Texture Measurement for Additive Manufacturing
- **Adam Thompson**, University of Nottingham
Internal geometry measurement for Additive Manufacturing
- **Professor Richard K. Leach**, University of Nottingham
In-Process Measurement and Future Look

Welcome and Opening Remarks

Tuesday, June 28, 2016, 08:45 AM - 09:00 AM

Session Chair: John S. Taylor, Lawrence Livermore National Laboratory

Session I

Industrialization of Additive Manufacturing

Tuesday, June 28, 2016, 09:00 AM - 10:40 AM

Session Chairs: John S. Taylor, Lawrence Livermore National Laboratory and
Ola L. A. Harrysson, North Carolina State University

- 1. Industrialization of Additive Manufacturing: Past, Present, and Exciting Future***
Herderick, E. C. (GE Corporate Supply Chain and Operations)
- 2. Reproducibility of the Dimensional Accuracy: Investigations for Fused Deposition Modeling**
Knoop, F.; Lienenke, T.; Schoepner, V. (University of Paderborn) 3
- 3. Dimensional Tolerances for Additive Manufacturing: Experimental Investigation of Manufacturing Accuracy for Selective Laser Melting**
Lienenke, T.; de Groot, S.; Adam, G. A.O.; Zimmer, D. (Paderborn University) 9
- 4. Characterization of Electron Beam Melting Process (EBM): Capability Approach**
Dolimont, A.; Rivière-Lorphèvre, E.; Ducobu, F.; Filippi, E. (University of Mons);
Michotte, S. (Sirris); de Formanoir, C.; Godet, S.; (Université Libre de Bruxelles). 16

Session II

Meeting Tolerances with Secondary Operations & Gauging

Tuesday, June 28, 2016, 11:10 AM - 12:25 PM

Session Chair: Michael M. Kirka, Oak Ridge National Laboratory and
Richard K. Leach, University of Nottingham

- 1. Laser Polishing of Additive Manufactured Steel and Titanium Components**
Smith, B.; See, T.; Hiersemenzel, F.; Antar, M. (Manufacturing Technology Centre);
Kaja, K. (Bruker UK Limited) 22
- 2. Integrating Metal AM with Milling and Non-Traditional Machining to Improve Surface Properties**
Iquebal, A. S.; Wang, Z.; Bukkapatnam, S. (Texas A&M University);
Shrestha, S.; Manogharan, G. P. (Youngstown State University) 28
- 3. "Additive is Not an Island" – A Renishaw Solution Approach to the Control of AM Part Quality**
McClelland, M. (Renishaw plc) 33

Commercial Announcements & Short Notes

Tuesday, June 28, 2016, 01:55 PM - 03:25 PM

Stephen J. Ludwick (Aerotech, Inc.) and
Seno Rekawa (Lawrence Berkeley National Laboratory)

Technical Poster and Networking Session

Tuesday, June 28, 2016, 03:40 PM - 05:10 PM

Session Chair: Wendy L. Shearon, American Society for Precision Engineering

- 1. Evolution of Surface Texture and Cracks During Injection Molding of Fiber-Reinforced, Additively-Manufactured Injection Molding Inserts**
Hofstätter, T.; Mischkot, M.; Pedersen, D. B.; Tosello, G.; Hansen, H. N.
(Technical University of Denmark) 38
- 2. Distribution and Orientation of Carbon Fibers in Polylactic Acid Parts Produced by Fused Deposition Modeling**
Hofstätter, T.; Pedersen, D. B.; Tosello, G.; Hansen, H. N. (Technical University of Denmark);
Gutmann, I. W. (University of Vienna); Koch, T. (Vienna University of Technology)
Heinz, G. (Karl Landsteiner University of Health Sciences) 44
- 3. Design of Artifact for Additive Manufacturing in the context of Aerospace Design***
Massey, M. D. (University of Tennessee-Knoxville); Kirka, M. M.;
Dehoff, R. R.; Babu, S. (Oak Ridge National Laboratory)
- 4. Surface Finish Metrology of Additive Manufactured Components**
Reese, Z.; Taylor, J. S.; Evans, C. J. (University of North Carolina-Charlotte) 50
- 5. Surface Finish Inspection by X-ray Computed Tomography in FDM Parts**
Ruiz-Huerta, L.; Castro-Espinosa, H. A.; Caballero-Ruiz, A.
(Universidad Nacional Autónoma de México) 55
- 6. Correlation Between Building Parameters, Mechanical Properties and Building Time In**
Ruiz-Huerta, L.; Gutiérrez-Osorio, H.; Caballero-Ruiz, A.; Borja-Ramírez, V.
(Universidad Nacional Autónoma de México) 60
- 7. Computed Tomography Aided Porosity Comparison Between ABS Filaments and FDM Manufactured Pieces**
Ruiz-Huerta, L.; Hernández-Contreras, A.; Caballero-Ruiz, A.; Almanza-Arjona, Y. C.
(Universidad Nacional Autónoma de México) 66
- 8. Raster Analysis and Mechanical Behavior Prediction by FEM of FDM Process**
Ruiz-Huerta, L.; Sánchez-Balazar, L.; Caballero-Ruiz, A.; Velázquez-Villegas, F.
(Universidad Nacional Autónoma de México) 72
- 9. Information-Rich Approach to Non-Destructive Non-Contact Measurement Planning, Inspection and Verification for Additive Manufacturing**
Stavroulakis, P.; Bointon, P.; Southon, N.; Leach, R. K. (University of Nottingham) 78

City Club Raleigh

Tuesday, June 28, 2016, 6:30 PM – 9:00 PM, Wells Fargo Building – 28th Floor, 150 Fayetteville Street

(A short 5-10 minute walk from the Marriott) – Dress Code: Business Casual

The Networking Dinner is atop the 28th floor of the Wells Fargo Building at the City Club Raleigh. See the fabulous view of Raleigh while enjoying fun, food and fellowship. Plan to take the walk from the Marriott to the Wells Fargo Building along Fayetteville Street, a vibrant, active area of the city.

* No Abstract Available

Session III

Design for Additive Manufacturing

Wednesday, June 29, 2016, 08:30 AM - 10:35 AM

Session Chair: David B. Pedersen, TU Denmark and
Stephen J. Ludwick, Aerotech, Inc.

1. Entry Points for Metal Additive Manufacturing in Precision Equipment

Peijnenburg, A. T.; Wijnstok, C.; Oosterhuis, G. (VDL Enabling Technologies Group);
Vanloffelt, M. (3D Systems) 81

2. Dimensional Accuracy of Printed End Effector

Wijnstok, C.; Oosterhuis, G. (VDL Enabling Technologies Group);
Vanloffelt, M. (3D Systems); Fournier, S. (KLA-Tencor Corporation) 87

3. Lattice Structure Topology Optimization for Lightweight Additive

Manufactured Design: Experimental Validation and Dimensional Accuracy

Cheng, L.; To, A. C. (University of Pittsburgh); Belski, E.; Ludwick, S. J. (Aerotech, Inc.);
Oskin, J. (Oberg Industries) 93

4. Designing for Color in Additive Manufacturing

Eiríksson, E. R.; Luongo, A.; Frisvad, J. R.; Pedersen, D. B.;
Aanæs, H. (Technical University of Denmark) 98

5. Precision Locating of Additively Manufactured Parts Using Embedded Kinematic Couplings

Penny, R. S.; Hart, A. J. (Massachusetts Institute of Technology) 103

Session IV

In Situ Process Metrology 1

Wednesday, June 29, 2016, 11:05 AM - 11:55 AM

Session Chair: Ola L. A. Harrysson, North Carolina State University and
Edward D. Herderick, GE Corporate Supply Chain and Operations

1. Powder Bed Layer Geometry

McGlaufflin, M. L.; Moylan, S. P. (National Institute of Standards and Technology) 108

2. In-Situ Monitoring in Additive Manufacturing Using Contact Image Sensors

Pedersen, D. B.; Eiríksson, E. R.; Aanæs, H.; Hansen, H. N.
(Technical University of Denmark) 114

Session V

In Situ Process Metrology - 2

Wednesday, June 29, 2016, 01:25 PM - 03:05 PM

Session Chair: Ola L. A. Harrysson, North Carolina State University and
Edward D. Herderick, GE Corporate Supply Chain and Operations

- 1. In Situ Surface Metrology of Laser Powder Bed Fusion Processes Using Fringe Projection**
Zhang, B.; Ziegert, J. C.; Davies, A. D. (University of North Carolina - Charlotte) 119
- 2. In-Situ Temperature Measurement During the Electron Beam Melting Process of Inconel 718**
Dinwiddie, R. B.; Kirka, M. M.; Dehoff, R. R.; Lowe, L. E.; Marlow, G.
(Oak Ridge National Laboratory) 125
- 3. Quality Control by Artificial Vision of Additively Manufactured Objects in the Arcam Q10 Electron Beam Melting Process**
Paquit, V.; Dehoff, R. R.; Kirka, M. M. (Oak Ridge National Laboratory) 126
- 4. In-Process Sensing for Laser Powder Bed Fusion***
Kelly, S. M.; Boulware, P. C.; Cronley, L.; Firestone, G.; Marchal, J.; Reichert, C. (EWI)

Session VI

Functional Assessment of AM Components

Wednesday, June 29, 2016, 03:35 PM - 05:15 PM

Session Chair: David J. Bate, Nikon Metrology and
Gerrit Oosterhuis, VDL Enabling Technologies Group

- 1. Effect of the Surface Finish on the Corrosion Resistance of Direct Metal Laser Sintered Ti6Al4V**
Xu, Y.; Lu, Y.; Brown, C. A.; Sisson, R. D. (Worcester Polytechnic Institute) 127
- 2. The Effect of Laser Scan Strategy on Distortion and Residual Stresses of Arches made with Selective Laser Melting**
Bagg, S. (NASA); Kolbus, L.; Bunn, J. (Oak Ridge National Laboratory) 133
- 3. Anisotropic Tensile Testing of Additively Manufactured Parts with Varying Interior Raster Geometries by Low-Cost Fused Filament Fabrication Machines**
Yamamoto, B. E.; Trimble, A. Z. (University of Hawai'i at Mānoa) 139
- 4. X-ray Computed Tomography for Additive Manufacturing: Accuracy of Porosity Measurements**
Hermanek, P.; Zanini, F.; Carmignato, S.; Savio, E. (University of Padova) 146
- 5. Assessing the Structural Integrity of Additive Manufactured Metal Parts with X-Ray CT**
Villarraga-Gómez, H.; Ramsey, A. (Nikon Metrology); Seifi, M.; Lewandowski, J. (Case Western Reserve University); Uchiyama, Y. (Nikon Corporation) 151

Session VII

Characterization of Surface Topography

Thursday, June 30, 2016, 08:30 AM - 10:35 AM

Session Chair: Christopher J. Evans, University of North Carolina at Charlotte

John S. Taylor, Lawrence Livermore National Laboratory

- 1. Towards an Additive Surface Atlas**
Thompson, A.; Senin, N.; Leach, R. K. (University of Nottingham) 156
- 2. Areal Surface Texture Parameters on Surface**
Pagani, L.; Scott, P. J. (University of Huddersfield) 162
- 3. Preliminary Study Toward Surface Texture as a Process Signature
in Laser Powder Bed Fusion Additive Manufacturing**
Fox, J. C.; Moylan, S. P.; Lane, B. M. (National Institute of Standards & Technology) 168
- 5. On the Metrology of Surfaces Produced by Laser Melting of Powders**
Lemoine, A.; Mancini, M. P.; Velez, J. A.; Brown, C. A. (Worcester Polytechnic Institute) .. 174

Session VIII

CT Metrology

Thursday, June 30, 2016, 11:05 AM - 12:45 PM

Session Chair: Christopher A. Brown, Worcester Polytechnic Institute and

Richard K. Leach, National Physical Laboratory, UK

- 1. Practical Methods of Correcting X-ray CT Scans**
Bate, D. J. (Nikon Metrology) 180
- 2. A Systems Approach to Quantifying Uncertainty in X-ray Systems for Metrology**
Cuadra, J. A.; Panas R. M. (Lawrence Livermore National Laboratory) 18
- 3. Inspection of Embedded Internal Features in Additively Manufactured
Metal Parts Using Metrological X-ray Computed Tomography**
Kim, F. H.; Moylan, S. P. (National Institute of Standards and Technology);
Villarraga-Gómez, H. (Nikon Metrology, Inc.) 191
- 4. A New Scatter Correcting Technology for Industrial mini- and microCT of Large
Multimaterial or Highly Absorbing Samples***
Telesz, S. (GE Oil & Gas Digital Solutions)

* No Abstract Available

Session IX

Metrology Instruments

Thursday, June 30, 2016, 01:55 AM - 03:35 PM

Session Chair: Jason Fox, National Institute of Standards and Technology
and Herminso Villarraga-Gómez, Nikon Metrology, Inc.

- 1. Computed Tomography to Evaluate Large Area Projection
Micro-Stereo-Lithography (LAP μ SL)**
Dooraghi, A. A.; Cuadra, J. A.; Jackson, J. A.; Moran, B.; Panas R. M.
(Lawrence Livermore National Laboratory) 196
- 2. Assessment of Dimensional Measurement Tools to Measure Additively
Manufactured Metallic Parts**
Brown, S. B.; Sun, W.; McCarthy, M. B.; Woolliams, P. D.
(National Physical Laboratory) 200
- 3. Investigating the Capability of Microfocus X-Ray Computed Tomography
for Areal Surface Analysis of Additively Manufactured Parts**
Townsend, A.; Blunt, L. A.; Bills, P. (University of Huddersfield). 206
- 4. Effect of Rough Metal AM Surfaces on Laser Scanner Accuracy***
Srinivasan, H.; Harrysson, O. L. A.; Wysk, R.; Ambekar, R. (North Carolina State University)

Session X

Development of AM Processes

Thursday, June 30, 2016, 04:00 PM - 05:40 PM

Session Chair: Michael M. Kirka, Oak Ridge National Laboratory
Ola L. A. Harrysson, North Carolina State University

- 1. Dimensional Accuracy and Machine Variability of Titanium Parts Manufactured
using the EOS Direct Metal Laser Sintered (DMLS) Process**
Mitchell, W. F.; Reutzel, E. W.; Merdes, T. A.; Lang, D. C.
(The Pennsylvania State University) 211
- 2. Characterization of Additive Manufacturing Materials
Using Energy Dispersive Spectroscopy**
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Koch, R. D.; Van Slyke, S. E.; (Honeywell FM&T) 216
- 3. Metals Additive Manufacturing and Equipment Experience
from a Process Engineering Viewpoint***
Griffith, B. E. (Honeywell FM&T)
- 4. A Holistic Approach to Metals Processed Through Electron Beam Melting**
Kirka, M. M.; Dehoff, R. R.; Lee, Y.; Okello, A.;
Dinwiddie, R. B. (Oak Ridge National Laboratory) 220

No Host Closing Reception, 06:00 PM – 06:30 PM – 8:00 PM,

Clouds Brewing Co., 126 N. West Street

The is your opportunity to talk about what you've learned and make connections.

*** No Abstract Available**



Technical Papers

REPRODUCIBILITY OF THE DIMENSIONAL ACCURACY: INVESTIGATIONS FOR FUSED DEPOSITION MODELING

Frederick Knoop^{1,2}, Tobias Lieneke^{2,3} and Volker Schoeppner^{1,2}

¹Kunststofftechnik Paderborn (KTP)

²Direct Manufacturing Research Center (DMRC)

³Chair of Design and Drive Technology (KAT)

Paderborn University

Paderborn, North Rhine-Westphalia, Germany

INTRODUCTION

Fused Deposition Modeling (FDM) is an Additive Manufacturing (AM) technology, which is used for prototypes, single-part production and also small batch productions [1-4]. This production technique has the huge benefit that no forming tool is needed and thermoplastic parts can be built from the CAD model in a few steps [1, 4]. For end-use part production, it is important that designers know about the mechanical properties, surface characteristics and dimensional accuracy [2, 4]. Knowledge of dimensional deviations of the FDM process is necessary for designing interactions between two or more parts, for calculating fittings and to know about the achievable manufacturing accuracy. A major challenge is the reproducibility of the dimensional accuracy of FDM parts, which is presently unknown.

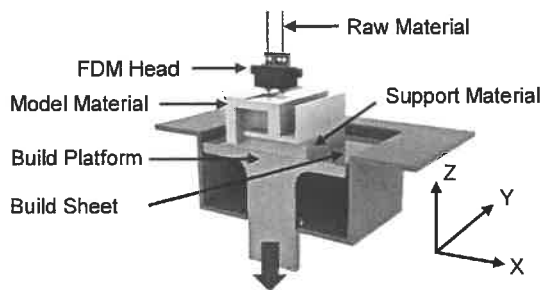


FIGURE 1. FDM process

The starting material in the FDM process is a strand-shaped thermoplastic. This is conveyed in the FDM head (cf. Figure 1). The material is melted in an extrusion nozzle by thermal energy. The continuous conveying of the strand has the effect that the molten plastic is pushed through the nozzle and finally emerges at the nozzle opening [4]. Through the motion of the FDM head in the X-Y direction, the emerging plastic strand is deposited in a defined manner. Once a layer has been completed, the build platform is lowered by the thickness of one layer

(Z-direction). The deposited strand is fused with the material beneath it through thermal conductivity [1]. The model material is used for the finished part, and the support material is needed to support overhangs or hollow spaces. Furthermore, the connection to the build platform is achieved with support material, which can be removed in an additional post-processing step by breaking it off or by dissolving it in an alkaline bath [1-3].

There are many influencing factors on the dimensional accuracy in the FDM process. There are geometric, material-specific, metrological, machine-specific, environmental and process technology influencing factors [5]. In this paper, geometric and process technology influencing factors are considered. First, the temperature distribution within the closed and active heated build chamber is measured. The aim is to determine if there is a relationship between the temperature distribution and occurring dimensional deviations over the entire build platform. The influence of the part position on the build platform is analyzed in terms of the achievable dimensional accuracy. Afterwards, the long-term reproducibility of the dimensional accuracy is verified. This is to consider how external influences such as maintenance or modification of machine components affect the dimensional accuracy of the FDM process.

MATERIAL AND MACHINE

For the studies in this paper, a Stratasys Fortus 400mc (large) is used. The available build envelope is 406 x 355 x 406 mm. The material used for the specimens is a natural-color ABS-M30. This amorphous ABS material has 25 to 70 % higher mechanical properties than standard ABS [3]. ABS-M30 can be processed with four different layer thicknesses. The layer thickness set here is 0.178 mm, for which a T12 tip is used. As support material, the SR-30

material is used with a T12SR30 tip. The toolpath parameters correspond to the standard settings of the Insight Software 9.1. These are shown in Table 1-1. The specimens are manufactured with a complete solid inner filling and an air gap of 0 mm.

TABLE 1. The used toolpath and process parameters for producing the specimens of ABS-M30

Tip Size	Shrink Factor		Contour & Raster Width	Raster / Delta Angle
	XY	Z		
T12	1.0055	1.0059	0.3556 mm	45 ° / 90°

EXPERIMENTAL SETUP

Temperature Measurement

The temperature measurement is carried out with thermocouples of Type J, which consist of the materials Fe-CuNi as defined in DIN EN 60584. The range of application is defined as up to 600 °C and the threshold deviation is 1.5 °C across the entire measuring range. The measurements are read out with a frequency of 5 Hz from the DasyLab software and saved. In these tests, eight measuring elements are used that are attached to an ABS build sheet with heat-resistant Kapton tape (polyamide-based adhesive tape). The thermocouples are distributed over the build platform in such a way that, as far as possible, all the areas are covered (see Figure 2).

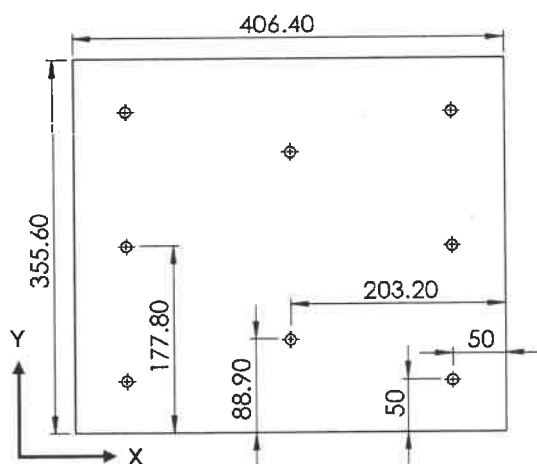


FIGURE 2. Arrangement of the thermocouples on the build platform (dimensions in mm)

In order to maintain the temperature distribution over the entire build platform, the non-measured areas are interpolated from the measuring points. For the temperature measurement of the entire build envelope, the build platform is moved to various Z-heights. In addition to the highest position in the build envelope (0 mm – directly below the extrusion nozzles) it will be also moved to the lowest position at Z = 406 mm.

Dimensional Accuracy

To determine the dimensional accuracy of FDM parts, specimens are designed with a cross-sectional area of 10 x 10 mm. The length of the samples is varied between 3 and 80 mm. The different nominal lengths are derived from DIN EN ISO 286-1. In the DIN standard, the nominal lengths are subdivided into classes, and in these investigations, the maximum of each class is always selected. The samples are aligned in the FDM process with their nominal length along the spatial axes X, Y and Z. Consequently, the alignments X and Y describe specimens that are lying flat, and the Z-alignment describes specimens that are standing vertically. In order to examine the reproducibility of the dimensional accuracy over the entire build platform, it is divided into nine areas. In each of these areas, an identical arrangement of the specimens is positioned so that the positions can be compared with each other. Figure 3 shows the arrangement of the test specimens on the build platform from above. Furthermore Figure 3 shows the position numbers 1 to 9. In order to enhance part quality, a sacrificial tower is added. The deposition of the filament in each new layer is performed initially on this part, thus ensuring a constant and homogeneous output of material from the extrusion nozzle.

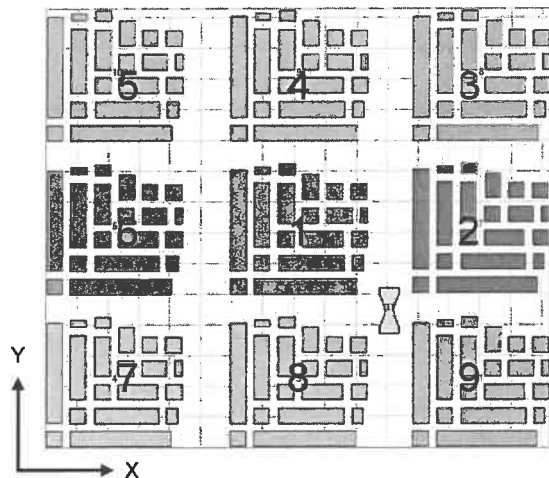


FIGURE 3. Arrangement of the test specimens and definition of the nine positions for the examination of the dimensional accuracy

For the sake of statistical certainty, the build job was manufactured six times on the same FDM system with the same material batch. For the nominal length of 10 mm, this gives a cube with an edge length of 10 mm, on which all three spatial directions are measured. Consequently, this results in 171 specimens per build job, which are conditioned for 88 hours at 23 °C and an atmospheric humidity of 50 % (according to DIN EN ISO 291). The specimens are measured with outside micrometers according to DIN 863, which are coordinated to the respective measuring area. The outside micrometers have the advantage that, because of an overload coupling, a defined force is applied for measuring the specimens. This results in very good reproducibility and a measuring accuracy of ± 0.01 mm. Per specimen, three local measurements are taken. The first measuring point is situated on the weld line of the outer contour, the second measuring point is in the middle of the specimen and the third is diagonally opposite the first measuring point. To determine the dimensional accuracy, the dimensional deviation is determined by subtracting the measured length from the respective nominal length.

To examine the long-term reproducibility, the previously described build job is manufactured again after one year with the same material and then evaluated. Over this period, there was a maintenance on the FDM system and the FDM head was replaced.

HEATMAPS

From the temperature measurements, heatmaps are compiled in order to produce a better visualization of the temperature distribution. The values of the eight measuring points are mean values over the total measuring period of 20 minutes, and the standard deviation during this period is ± 0.37 °C. The areas between the measuring points are interpolated bilinearly and a conditional formatting is applied. The highest temperatures are colored red and the lowest temperatures blue, so that easier comparability between the heatmaps is possible. The target temperature in the build envelope with the material ABS-M30 and a T12 tip is 90 °C. Upper left is the air exhaust vent of the heated air in the build envelope. Through the opening top right, the air can escape again, is reheated by heating elements and again turned into a convective flow through two fans. Within the build envelope, there is a temperature sensor positioned in the top left corner of the build envelope. Because the temperature sensor is positioned directly in front of the aperture, the temperatures within the build envelope can differ. This is clearly recognizable in Figure 4 for the highest position of the build platform, which corresponds to a Z-position of 0 mm.

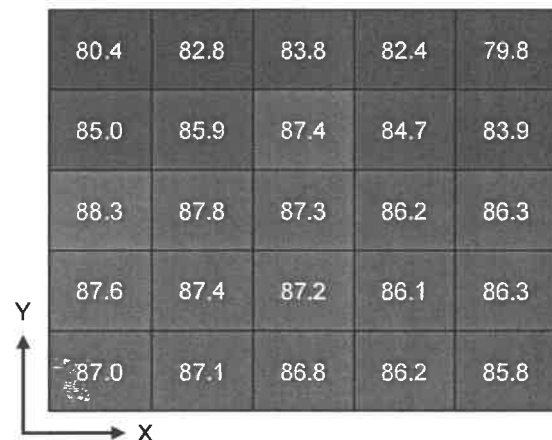


FIGURE 4. Heatmap for Z-position of 0 mm (in °C – top view)

Furthermore, the air exhaust vent is not designed to be covering the whole width of the build envelope so that cooler areas are created in the rear part of the build platform. The lowest value was measured in the rear right-hand corner and is 79.8 °C, which is around 10 °C below the target temperature. The rear left-hand corner also has a very low temperature. The

maximum is on the left-hand side, directly in front of the air exit, namely 88.3 °C. The mean temperature over all 25 areas is 85.6 °C, although account should be taken of the inhomogeneous temperature distribution. If the build platform is in a Z-position of 5 mm, the average temperature is 84.6 °C. With increasing Z-position (which corresponds to a lowering of the build platform), the temperature also begins to decrease. From a Z-position of 10 mm, the warmest part turns out to be in the middle area of the build platform. This picture changes from a height of approx. 100 mm because the scatter is lower and the temperature is at a mean value of 80.8 °C (cf. Figure 5). The warmest areas are now in the rear right-hand area and the coldest area is front left, near the build envelope door. On lowering it further to the lowest Z-position of 406 mm, the mean temperature drops to 78.3 °C, and the range of the measurements also decreases to give a more homogeneous temperature range.

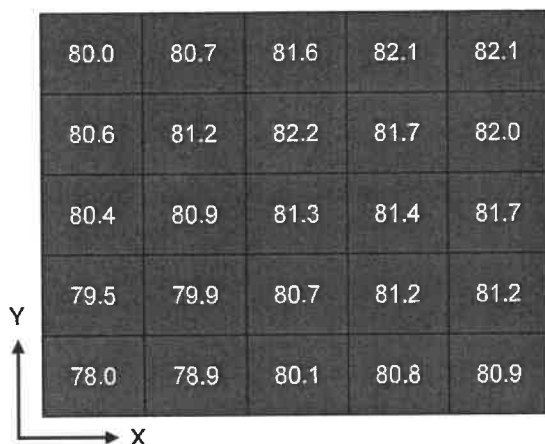


FIGURE 5. Heatmap for Z-Position of 100 mm (in °C – top view)

DIMENSIONAL ACCURACY

With the aid of the compiled heatmaps, possible relationships between dimensional deviations and ambient temperature in the build envelope of the Fortus 400mc are to be determined. In diagrams Figure 6 to Figure 8, the dimensional deviations of all nominal lengths are plotted for each of the nine part positions. For the sake of clarity, the standard deviations have not been plotted in the diagram, although it can be said that the standard deviation average is ± 0.04 mm for all measuring points. From Figure 6, the dimensional accuracy can be read off for samples that were aligned along the X

axis. It is obvious that the dimensional deviations rise with increasing nominal length. For the largest nominal length of 80 mm, dimensional deviations of between 0.08 and 0.15 mm occur, and for a nominal length of 3 mm, the deviations are between 0.04 and 0.01 mm. Furthermore, a slightly wave-like shape of all the curves is evident. At positions 2 and 9, local minima can be identified, but because of the very small differences in the dimensional deviations and taking the standard deviation into account, it is impossible to ascertain any systematic influences. Furthermore, no connection can be derived between the build envelope positions with higher or lower temperatures and the dimensional deviations occurring there.

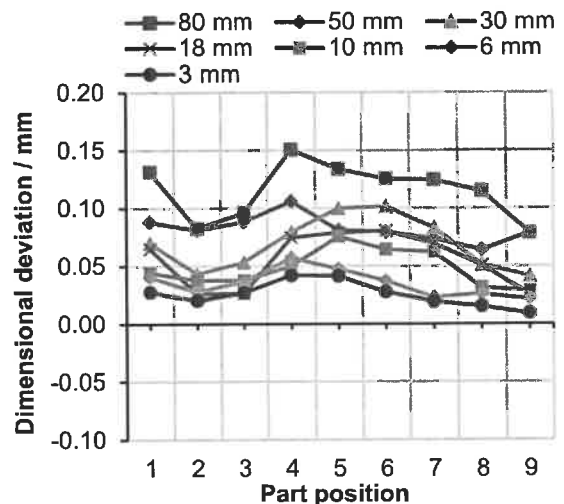


FIGURE 6. Reproducibility of the dimensional accuracy in X-alignment.

In the next step, the dimensional deviations were investigated for specimens aligned along the Y axis (see Figure 7). It can be seen that the deviations can be found this time in a slightly different area, namely with negative values up to -0.03 mm (80 mm nominal length) and maximum deviations up to 0.08 mm (50 mm nominal length). The dimensional deviations presented here indicate an anisotropy of the geometric accuracy in X and Y. For the nominal lengths of 3, 6 and 10 mm, no deviations occur in the mean values across the nine positions. The nominal lengths of 50 and 80 mm indicate higher average values at positions 7 to 9. Taking the standard deviation into account, it is impossible to formulate any clear regularity.

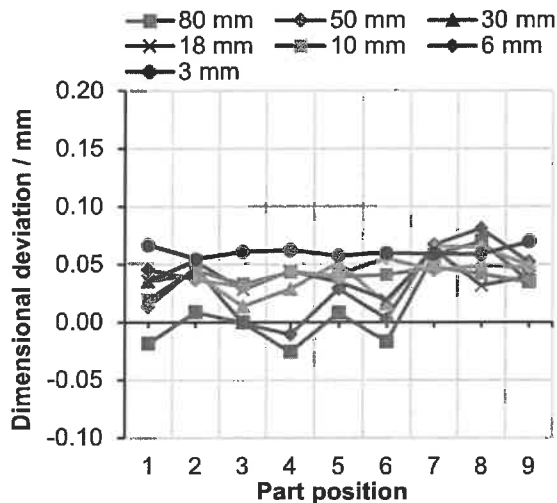


FIGURE 7. Reproducibility of the dimensional accuracy in Y-alignment.

The vertically built specimens, i.e. aligned along the Z-axis, show exclusively positive dimensional deviations (cf. Figure 8). Because, in view of the layer structure, an approximation of the nominal length is made, the dimensional accuracy is dependent on it. This results in a small nominal length of 10 mm showing similar deviations to the specimens with a nominal length of 50 mm. The maximum deviations here are 0.30 mm and the lowest deviation comes from the nominal length of 3 mm with 0.09 mm. All nominal lengths show a virtually identical curve with a local minimum at positions 3 and 4. The temperature measurements have shown that, at these positions, comparatively lower temperatures prevail when the build platform is located between 0 and 20 mm (Z-position). This trend may be an indication for the fact that areas with lower temperatures tend to lower deviations in the Z-direction. At position 7, many nominal lengths show the highest average deviations. This area of the build platform shows comparatively higher temperatures so that the previously made supposition is confirmed by this observation.

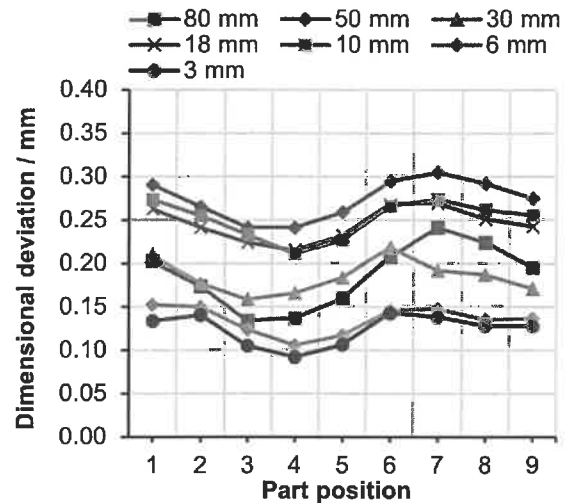


FIGURE 8. Reproducibility of the dimensional accuracy in Z-alignment.

LONG-TERM REPRODUCIBILITY

Now that the reproducibility has been examined over the entire build platform, the next step involves examining the long-term reproducibility. From the nine positions, an individual mean value is now calculated for each nominal length. In Figure 9, the mean dimensional deviations are plotted in a line chart against the respective nominal length. The blue curve describes the initial state, made up of six build jobs. The red curve illustrates the dimensional deviations from the build job that was manufactured one year later. The averages of the initial state are slightly below the state after one year. The differences for all nominal lengths are, however, very small and are max. 0.03 mm. If the standard deviation and thus the scatter of the measurements is taken into account, no differences can be detected. Furthermore, the state after one year was determined by one build job, so that this is also subject to certain fluctuations within the standard deviation.

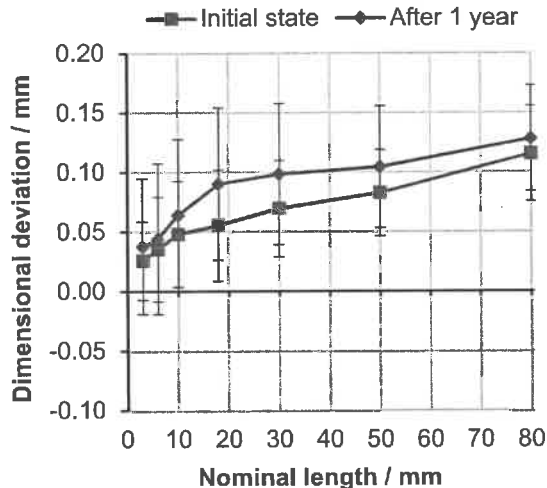


FIGURE 9. Reproducibility of the dimensional accuracy in X-alignment.

The results of the long-term reproducibility in the Y and Z-directions harmonize with the results of the X-direction from Figure 9. In the Y direction, the mean deviations of the short nominal lengths up to 10 mm are also at one level. The higher nominal lengths show very small differences of approx. 0.03 mm and are thus also within the standard deviation (± 0.04 mm). The evaluation for the Z-aligned specimens does not show any differences in the dimensional deviations. Virtually identical measurements were determined for all nominal lengths. On the basis of these results, very good reproducibility of the dimensional accuracy can be determined if certain boundary conditions (same FDM system and same material batch) are adhered to.

CONCLUSIONS

In this publication, the reproducibility of the dimensional accuracy for Fused Deposition Modeling was investigated. In the first step, the temperature distribution in the build envelope of a Stratasys FDM system of Type Fortus 400mc was examined. The compiled heatmaps were able to visualize the in some cases rather inhomogeneous temperature distribution. If the build platform is located at a Z-height between 0 and 10 mm, colder areas can be detected in the rear area. The dimensional accuracy of the process was examined through a build job that fills up the entire build platform. Here, the aim was to analyze the reproducibility in terms of the dimensional accuracy over the entire build platform. It was found that there is good reproducibility along the dimensional axes X, Y and Z. At the same time, however, a certain

scatter of the measurements must be taken into account, which is presumably induced among other things by the inhomogeneous temperature distribution. Subsequently, the long-term reproducibility was examined after one year. Here it was found that, with this FDM system, very reproducible dimensional deviations occur.

ACKNOWLEDGEMENTS

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DIMENSIONAL TOLERANCES FOR ADDITIVE MANUFACTURING: EXPERIMENTAL INVESTIGATION OF MANUFACTURING ACCURACY FOR SELECTIVE LASER MELTING

Tobias Lieneke^{1,2}, Stefan de Groot^{2,3}, Guido Adam² and Detmar Zimmer^{1,2}

¹Chair of Design and Drive Technology (KAT)

²Direct Manufacturing Research Center (DMRC)

³Chair of Automotive Lightweight Construction (LiA)

Paderborn University, Faculty of Mechanical Engineering,
Paderborn, North Rhine-Westphalia, Germany

INTRODUCTION

Additive manufacturing (AM) processes create metal or plastic parts and assemblies in layers without using formative tools [1, 2]. Due to the manufacturing principles, these processes offer a number of great advantages compared to established processes, such as a high level of function integration or the design freedom. However, only a limited number of research institutes and technology-leading companies use additive manufacturing for end-use part production [3].

In this publication, the additive manufacturing process Selective Laser Melting (SLM) is considered in terms of the achievable manufacturing accuracy. A schematic representation of the SLM process is shown in FIGURE 1.

non-melted powder remains within the build chamber and serves as disperse support material. After a layer exposure, the build platform is lowered by one layer thickness in the z-direction to create space for the application of a new layer of powder. This cycle is repeated until the part is completed [1, 2]. The process is carried out without any pre-heating of the powder. The large energy input results in a high temperature gradient within the build chamber and causes residual stresses on laser-melted parts. Thus, solid support material is needed to connect the parts to the build platform and to allow the heat in the actual layer to dissipate. Additionally, the build platform can be heated to reduce residual stresses. After the building process, non-melted powder and solid support material have to be removed.

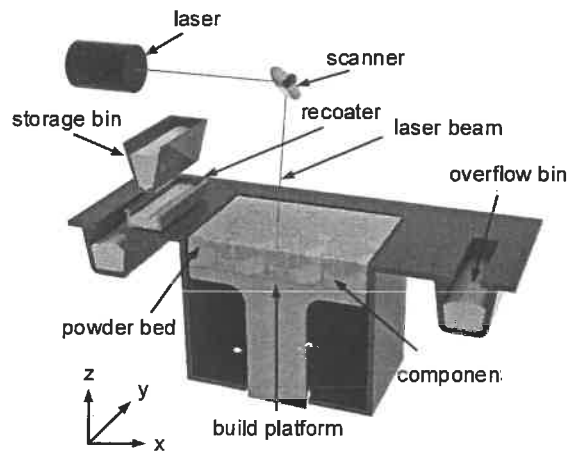


FIGURE 1. Schematic representation of SLM

The SLM process rests on the use of metal powder. In a first step, the powder is applied layer-wise in the x-y plane by a re-coater. Next, the laser contributes temporal and local energy to generate the melting of powder particles. The

Motivation and objectives

Through the layer-by-layer manufacturing, new technical and economic benefits can be gained. In technical terms, the great design freedom is one of the potentials most worth mentioning [4]. In economical ways, manufacturing costs can be decoupled from the complexity of the component [5], which increases the industrial demand for additive manufacturing [6].

Despite these benefits, the usage of additive manufacturing for end-use part production purposes is still limited [3]. The reason is that additive manufacturing involves different process-specific challenges that harm the industrial establishment such as rough surfaces or the stair-stepping effect at orientated surfaces [7]. Furthermore, the end-use part production requires an accurate knowledge and understanding of all restrictions and possibilities, especially during the product design and development process [8]. Therefore, the geometrical accuracy constitutes an important quality characteristic and a great challenge in

the further determination and improvement [4, 9]. For this purpose, the project "Dimensional Tolerances for Additive Manufacturing" (DT-AM) at the "Direct Manufacturing Research Center" (DMRC) of Paderborn University started to explore dimensional tolerances regarding two main objectives. First, achievable dimensional tolerances shall be systematically determined, that can be specified, if additive manufacturing is used under standard conditions, meaning the application of often used and established standard parameters, materials and machine settings. Second, relevant process parameters and manufacturing influences are investigated to define measures that are utilized to minimize dimensional deviations. The present publication concentrates on both objectives and is focused on SLM.

Proceeding

To investigate the dimensional accuracy for additive manufacturing and to deduce achievable dimensional tolerances, the state of the art is reviewed first. Based on the gained knowledge, a new method is developed that can be used to analyze the dimensional accuracies for additive manufacturing systematically. This method defines relevant influential factors on the dimensional accuracy. Afterwards, the occurring deviations are detected through experimental tests.

STATE OF THE ART: MANUFACTURING ACCURACY OF AM

The following paragraphs give a brief overview of the current state of the art of the geometrical accuracy for SLM. After the presentation of process-independent benchmark studies, this chapter concentrates on SLM.

Benchmarking the geometrical accuracy

Literature demonstrates a variety of research activities of benchmarking the geometrical accuracy for several prominent processes. These studies focus on aspects such as repeatability, building speed and feasibility of minimum feature size to compare available processes and machines [10-21]. Beside these publications, process-specific investigations on occurring geometrical deviations and concepts to optimize the accuracy are known and presented in the following.

Geometrical tolerances for SLM

COOKE and SOONS investigate deviations of dimension, form and location for SLM and

Electron Beam Melting (EBM) [22]. Based on one test specimen, they also analyze the influence of different heat treatments on the occurring deviations. For instance, the tested nominal dimension of 100 mm along the x- and y-axes shows deviations between -0.2 mm and +0.1 mm in the x-direction and -0.2 mm and +0.05 mm in the y-direction. The circularity exhibits tolerance zones between 0.094 mm and 0.156 mm, which are calculated between the minimum and maximum deviation [22]. Beside COOKE and SOONS, HANUMAIHAH investigates form and location deviations and derives tolerances for Direct Metal Laser Sintering (DMLS). A straightness tolerance of 0.0372 mm is defined. The deviations for flatness are examined within a tolerance of 0.0868 mm and the circularity tolerance is estimated to be 1.5320 mm [23]. Apart from these publications, many researchers strive to optimize the geometrical accuracy. For instance, JACOBS [24] and NING et al. [25] execute investigations to minimize build errors and deviations by analyzing the shrinkage behavior and present optimization potentials.

The abovementioned literature demonstrates a large variation of observed geometrical deviations. These differences can be explained by the boundary conditions used and the large number of factors influencing the geometrical accuracy [24-27]. Therefore, it is difficult to compare individual investigations with different processes, materials, machine settings and test specimens. This fact highlights that there is no generally known, reliable and comprehensive information about tolerances for additive manufacturing processes - neither in literature nor in standards.

Thus, a method is to be developed to examine dimensional deviations and to derive realistic tolerance values. The method shall be universally applicable to additive manufacturing processes.

METHODICAL BACKGROUND AND EXPERIMENTAL SETUP

The first objective of this investigation is the systematical and experimental determination of dimensional deviations for the SLM process. Next, process parameters and manufacturing influences are considered experimentally to find a way to minimize the occurring dimensional deviations. A systematical determination and minimization of dimensional deviations requires a methodical procedure; this is briefly introduced in the following [25, 26, 28].

Boundary conditions

In this paper, the manufacturing system SLM 280^{HL} from SLM Solutions is used for the experimental tests. The available build envelope is 280 x 280 x 365 mm. For the manufacturing of test specimens, the stainless steel 316L (1.4404) is applied. The material achieves a tensile strength of 633 MPa and an elongation at break of 30 %, when it is manufactured with SLM [25]. For the investigation of the manufacturing accuracy at the current state of the art, the process parameters are held constant at standard values. The layer thickness is executed with 0.05 mm and the shrink factors are set at 0.223 % for all axes. To identify the influence of process factors and to minimize the dimensional deviations, different process parameters are varied.

Influential factors

First, relevant factors influencing the dimensional accuracy are identified by a literature research. Next, the results are expanded with process experts from industry and science. The result is an Ishikawa diagram for SLM, which lists numerous factors influencing the dimensional accuracy. Due to the large number of factors, the most relevant influencing factors are selected. The remaining factors can be classified into two main groups, which correspond with the two project objectives. For the determination of achievable dimensional tolerances, geometrical factors are considered in detail. To achieve a minimization of the occurring dimensional deviations, the process factors are investigated experimentally. The selected geometrical and process factors are represented in FIGURE 1 and 2.

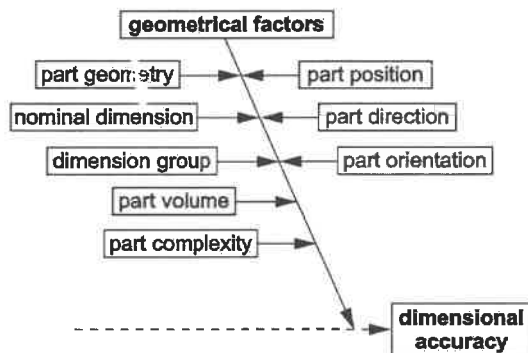


FIGURE 1. Selected geometrical factors

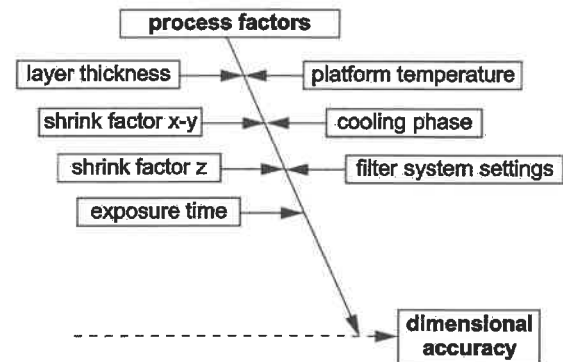


FIGURE 2. Selected process factors

Definition of variation ranges

For the experimental investigation, variation steps are defined for the selected influencing factors. The underlying paper focuses on the geometrical factors: nominal dimension, part orientation and direction, and the part position in the build chamber. To investigate the influence of process parameters, the factors layer thickness, platform temperature, and shrink factors are considered within this publication.

The variation of the nominal dimension is derived from DIN EN ISO 286-1 [38]. According to this standard, the nominal dimension is varied by 3, 6, 10, 18, 30, 50, and 80 mm. The consideration of different orientations and directions in the build chamber is analyzed by three spatial alignments. Therefore, the nominal dimension is aligned along the x-, y- and z-axes (FIGURE 3). Due to different temperature gradients within the build chamber, the position of the parts is supposed to influence the dimensional accuracy. To examine the position influence, nine different positions in the x-y plane are investigated (FIGURE 3).

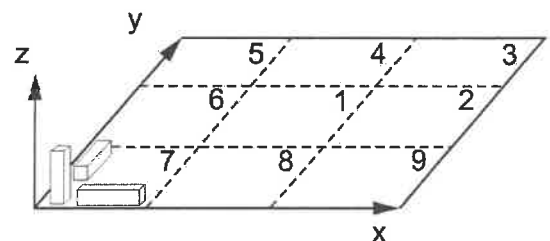


FIGURE 3. Selected positions and alignments

The selected process factors guarantee that the exposure strategy and the volume energy density can be kept constant during manufacturing. Thus, the mechanical properties of the material are not influenced due to the

experimental variations. The layer thickness is varied by 0.03 and 0.05 mm. The platform temperature, which is used to reduce the residual stress in parts, is altered from room temperature to 100°C and 200°C, respectively. Furthermore, the shrink factors in the x-, y- and z-axes are investigated at 0.000%, 0.075% and 0.113%. The design of experiment (DoE) method by Taguchi is used to identify a possible optimum of these factors.

Test specimen and measurement

The applied method presents a test specimen with a corresponding suitable measurement technique. The underlying investigation is based on cuboids with a cross sectional area of 10 by 10 mm and nominal dimensions according to DIN EN ISO 286-1 [30]. The test specimens are measured in the x- and y-alignment by micrometer screws with an accuracy of 0.01 mm. Test specimens in the z-alignment are manufactured directly on the build platform to avoid an influence of the support material onto the dimensional accuracy. Previous studies have shown that the solid support material cannot clearly be separated from the part and a machining of surfaces with solid support material is recommended [15]. Because the test specimens are manufactured directly on the build platform, an additional measurement method is needed. In this case, a coordinate measuring machine Nikon Altera 8.7.6 is used.

On each test specimen, three local dimensions over the diagonal of the cross sectional area are recorded. The global dimension of one test specimen is evaluated as the minimum, maximum or mean value of the three local dimensions.

EXPERIMENTAL INVESTIGATION

Based on the developed method, the determined deviations allow the derivation of achievable dimensional tolerances for SLM. In the following sections, the experimental results for varying geometrical and process factors are presented.

Geometrical factors

In this section, the results of the experimental investigation of the considered geometrical factors are presented.

Figure 4 shows the average values of the occurring local deviations (y-axis) versus the

nominal dimensions (x-axis). Additionally, the linear trend line for each alignment (x, y, and z) is shown. The results were averaged over all considered positions. Each test specimen was manufactured three times for each nominal dimension, alignment and position.

In the x- and y-alignment, a falling trend of the average deviation is evident dependent on the nominal dimension. The averaged deviations range between +0.06 mm and -0.22 mm. In the z-alignment, the dimensional deviations can be indicated with a trend from -0.39 mm to -0.19 mm with increasing nominal dimension. Further investigations show that the different deviations in the x-, y-, and z-alignment are mainly caused by material shrinkage. Thus, the shrink factors in the x-, y-, and z-alignment, which compensate the material shrinkage, show a noticeable optimization potential; this is considered in terms of the process parameters in the next section.

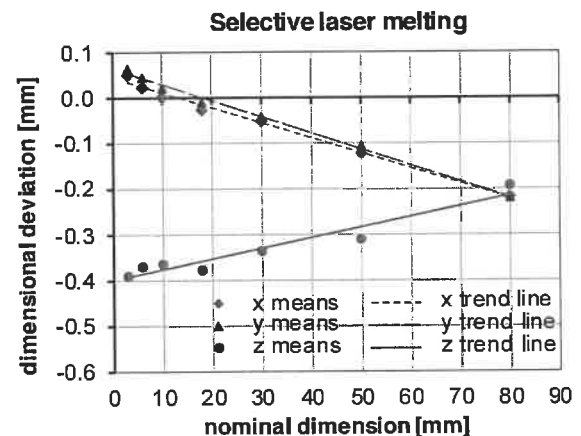


FIGURE 4. Means of the dimensional deviations in x-, y-, and z-alignment for SLM

To derive dimensional tolerances for SLM, the occurring minimum and maximum of all locally measured deviations are used. FIGURE 5 shows the minimum and maximum values of the measured local dimensions in the x-, y-, and, z-alignment. The diagram represents the tolerance range depending on nominal dimension and spatial alignment. The course of the minima and maxima is shown by trend lines (FIGURE 5).

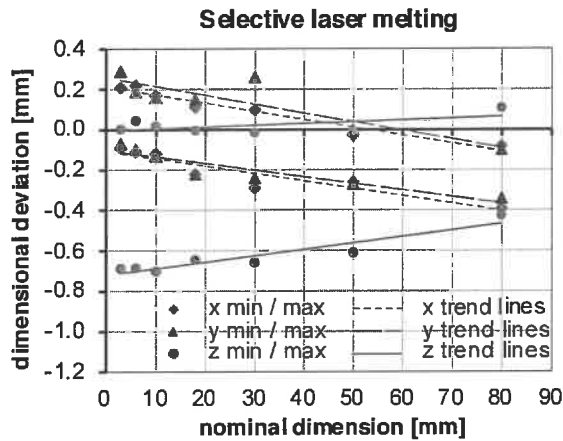


FIGURE 5. Minima and maxima of the local dimensional deviations in x-, y-, and z-alignment for SLM

The largest range (0.39 mm) for the x-aligned test specimen is indicated for the nominal dimension of 30 mm between the minimum of -0.29 mm and the maximum of +0.10 mm. In the y-alignment, the largest tolerance range is detected for the nominal dimension of 30 mm with a value of 0.50 mm. The associated minimum and maximum are described by the values -0.24 mm and +0.26 mm. Similarly, test specimens in the z-alignment show the largest deviation range of 0.73 mm between the minimum of -0.68 mm and the maximum of +0.05 mm. Contrary, the smallest ranges are identified with 0.23 mm (50 mm in x-alignment), 0.24 mm (80 mm in y-alignment) and 0.53 mm (80 mm in z-alignment). In sum, the results emphasize that the nominal dimension and the spatial alignment show the greatest influences on the dimensional accuracy. In contrast to this, the investigation of different positions on the build platform (not presented) shows that the position does influence the dimensional accuracy, but a clear correlation between occurring deviation and defined position is not apparent.

Process factors

The second objective strives to improve dimensional accuracy by optimizing relevant process parameters and manufacturing influences. In order to minimize the occurring dimensional deviations, the influence of various factors is identified first. After that, four parameters are stated to determine and improve dimensional deviations by using the design of experiment method of Taguchi. Nominal

dimensions of 3, 6, 10 and 18 mm in the x-, y- and z-alignment are considered and the parameters layer thickness, platform temperature, shrink factor in the x-y-alignment and z-alignment defined. Thus, a Taguchi test series is executed by analyzing combinations of nine factors (TABLE 1), which are manufactured three times with regard to the confidence level. The occurring dimensional deviations of the Taguchi series are analyzed to achieve an optimum set of process factors to improve dimensional accuracy.

TABLE 1. Factor combinations according to Taguchi DoE

Trial no.	Layer thickness [μm]	Platform heating [°C]	Shrink factor [%]	
			x-y	z
1	30	rt	0	0
2	30	100	0.075	0.075
3	30	200	0.113	0.113
4	50	rt	0.075	0.113
5	50	100	0.113	0
6	50	200	0	0.075
7	50	rt	0.113	0.075
8	50	100	0	0.113
9	50	200	0.075	0

By using Taguchi DoE, the results of the Taguchi test series are analyzed for each nominal dimension and alignment in order to calculate an optimum set of factors. At the same time, the influence of each process factor is identified. The factors platform temperature and shrink factor for the x-y-alignment significantly influence dimensional accuracy, especially for large nominal dimensions. Another effect is identified for the shrink factor in the z-alignment. In this context, it is not possible to detect a recognizable influence of layer thickness on dimensional accuracy. Based on these results, an optimum set of the considered process parameters can be identified (TABLE 2).

TABLE 2. Optimum set of process factors according to Taguchi DoE

Process factor	Optimum set
Layer thickness [μm]	50
Platform temperature [°C]	100
Shrink factor x-y-alignment [%]	0.113
Shrink factor z-alignment [%]	0.075

CLASSIFICATION INTO ISO TOLERANCE SYSTEM

The defined tolerance ranges for the geometrical factors are classified into the ISO tolerance (IT) classes according to DIN EN ISO 286-1 and compared to established manufacturing processes. The results show that SLM achieves IT classes between 12 and 17 depending on the chosen alignment (TABLE 3).

TABLE 3. IT classes for SLM depending on nominal dimension and alignment

Nominal dimension [mm]	IT class		
	x	y	z
3	IT15	IT15	IT17
6	IT15	IT14	IT16
10	IT14	IT14	IT16
18	IT14	IT14	IT15
30	IT14	IT14	IT15
50	IT12	IT13	IT14
80	IT13	IT12	IT14

The achievable manufacturing accuracy of SLM, illustrated by the IT classes (TABLE 3), is compared to established manufacturing processes. With the derived tolerance values, SLM is nearly comparable with casting, forging, cutting, and drilling with regard to the achievable dimensional accuracy (TABLE 4).

TABLE 4. Comparison of manufacturing accuracies for different processes according to the IT class system

Process	IT class								
	10	11	12	13	14	15	16	17	
Casting									
Forging									
Milling									
Cutting									
Drilling									
SLM									
x									
y									
z									

CONCLUSION AND OUTLOOK

In sum, the publication presents a first step in a systematical determination of dimensional deviations and achievable tolerances as well as a minimization of occurring dimensional deviations due to optimized process factor settings. The experimental results of this investigation show that SLM achieves IT classes between 12 and 17 under the considered standard boundary conditions. However, the DoE test series emphasize that the process factors provide an optimization potential in terms of the achievable dimensional accuracy.

In the next step, more geometrical factors will be considered in order to strengthen the basis of occurring deviations on different geometries. In terms of minimizing dimensional deviations, the defined optimum set of process factors has to be evaluated. With regard to the confidence level of these investigations, the test specimens have to be manufactured multiple times. After the evaluation phase, the results have to be classified into the ISO tolerance (IT) classes according to DIN EN ISO 286-1 and be compared to conventional manufacturing and further results as well.

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CHARACTERIZATION OF ELECTRON BEAM MELTING PROCESS (EBM) : CAPABILITY APPROACH

Adrien Dolimont¹, Sebastien Michotte², Edouard Rivière-Lorphèvre¹, François Ducobu¹, Charlotte de Formanoir³, Stéphane Godet³ and Enrico Filippi¹

¹Machine Design and Production Engineering Lab, Faculty of Engineering
University of Mons, Place du parc 20 7000 Mons (Belgium)

²SIRRIS collective centre for and by the technological industry
26 Rue Auguste Piccard, 6041 Gosselies (Belgium)

³Materials engineering, characterization, synthesis and recycling Lab
Faculty of Engineering - Université libre de Bruxelles, 1040 Bruxelles (Belgium)

INTRODUCTION

Initially used for rapid prototyping and product visualization, Additive Manufacturing (AM) technologies are more and more widespread [1]. These technologies permit now to produce real parts with required mechanical properties. Aerospace, biomedical and rapid tooling are fields where AM is widely used [2]. AM allows new ways of thinking by unlocking the design limitations encountered by other manufacturing methods. One of its biggest advantages is the production of near net shape reducing wastes and energy consumption. The Electron Beam Melting (EBM) is one of these technologies. EBM technology is a powder-bed-metal based additive manufacturing technique developed at Chalmers University of technology in the late 1990's and commercialized by the Swedish company Arcam AB in the early 2000's [3]. This process builds up a part layer-by-layer. The most widely used material for the EBM Process is Ti6Al4V. This is the material used in this study with standard processing parameters. EBM process is a near net shape process and it is necessary to carry out finishing operation after EBM (mostly machining). The goal of this research is to determine the class of tolerance of the EBM process by a capability approach. This approach allows to define the class of quality of the parts and so the machining allowance of the parts to avoid rejection at the subsequent machining post-processing operations [4] to have net shape parts.

LITERATURE REVIEW

Currently, some investigations are still required to ensure the quality and the consistency of the parts built by AM. So far, the standards in AM are slowly emerging and it is therefore important to investigate in this direction. In AM, there are several sources of errors and some authors have de-

termined them. Cooke et al. [5] categorized the errors in AM in 3 groups.

1. Errors originating from the equipment, such as errors in the pattern generated by the energy beam due to errors in the scanning unit and optical aberrations, the energy distribution of the beam focus spot and its layer height;
2. Errors due to the process, such as spot diameter, layer thickness, thermal expansion of the part during deposition, warping of the part during cool down, melt pool deformation and sag of overhang structures into the supporting powder;
3. Errors in the part model due to the approximation of curved surfaces with planar triangular patches.

With the development of AM technologies, it is possible to produce near net shape parts without special tool and the complexity of the parts does not influence the production cost. Those characteristics of the process provides big advantages against other subtractive processes. Figure 1 compares the advantage and drawback of producing final part from an EBM rough part. By the traditional way (from a raw part, Figure 1 a) there is a lot of extra material so we are sure to be in the desired tolerances after machining but the problem is that it produces a lot of waste. By the AM way, there is a reduction of the waste produces and a decrease of the machining time due to the near net shape process. But it must fit the desired tolerances (Figure 1 b). A tight control of the process is required for an efficient production of real near net shape parts. In order to keep

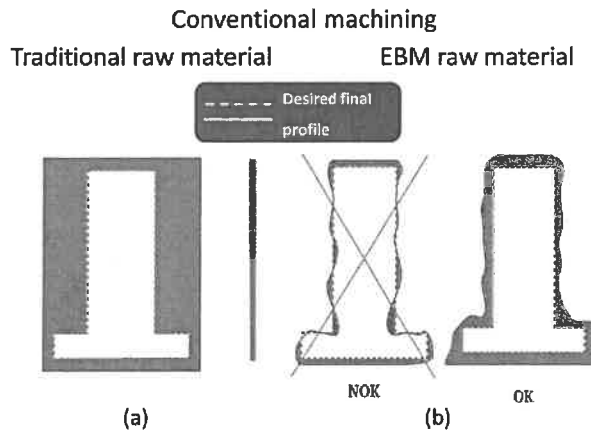


FIGURE 1. Machining operations are needed to obtain the final part. Comparison with traditional raw material (a) and EBM raw material (b) [6]

the advantages of AM, it is essential not to provide too large machining allowance, therefore the need to control them [6].

Test artifacts have been proposed by several authors to characterize the performance of additive processes. A state of the art can be found in ref. [6]. But until now, all those studies were performed on a limited number of parts (1 to 5 maximum). In this study, the characterization of the process is done on a large numbers of parts built by the EBM process. The parts were built in the same fabrication batch (two batches were also performed to evaluate the repeatability from one batch to another). The goal of our study is to further characterize the EBM process and determine the class of quality related to this process with different sizes of parts. To do this, a study of the dimensions obtained at the output of the process was carried out on a large number of parts (± 80).

This paper is the next step of the paper presented in International Journal of Rapid Manufacturing by Dolimont et al. [6].

MATERIALS AND METHODS

The EBM process was characterized on a large number of parts. The dimensional accuracy and surface roughness were determined after each batch of fabrication. This methodology highlights the class of quality of the process. By this technique, it is possible to compare EBM process with other manufacturing processes. The printer used to build the samples in this study is an Arcam A2. Parts were produced using Ti6Al4V alloy which

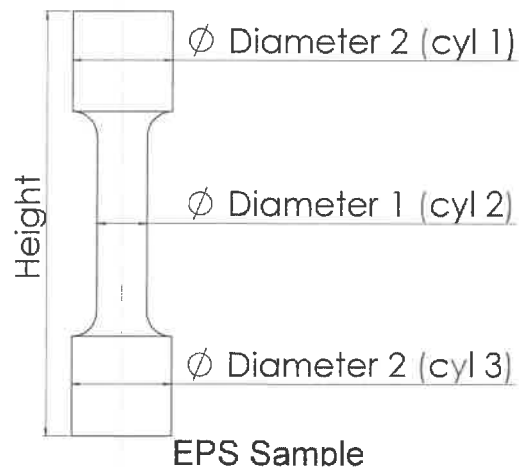


FIGURE 2. Tensile samples with different size [6]

is of the most commonly used titanium alloy in aeronautic industry. The samples, called in this study EPS, have 4 different dimensions with proportions kept according to ASTM E466 standard [7] (see Figure 2) for tensile tests performed in an other study [8]. Dimensions for the target values vary from 54.934 to 103.250 mm for the height and from 3.165 to 21.070 mm for the diameters.

The powder used in this study was Ti-6Al-4V spherical plasma atomized powder provided by Arcam, with a size distribution going typically from 45 to 106 μm and centered around 70 μm . This powder is recycled with fresh additions of ELI (grade 23) powder.

Standard settings were used with 70 μm layer thickness under a controlled vacuum of $2 \cdot 10^{-3} mbar$ of helium and with the Multibeam technology for the contours melting.

Dimensional and surface characterizations

A coordinate measuring machine (Wenzel LH 54, precision : $U_x, U_y (\mu m) = 3 + 10.L(mm)/3$ and $U_z (\mu m) = 3.5 + 10.L(mm)/3$) was used to determine the dimensions after each batch of fabrication. A spherical probe with a diameter of 2.5 mm was used to touch directly the part to define fundamental entities (plane, cylinder, etc.). By this method, the height (z direction) and the diameters (XY direction) were measured.

A surface roughness meter SURFCOM 1400D-3DF was used to determine the surface quality. The ISO 4288 standard [9] was followed for each measurement.

Capability approach

Kapadia [10] define the capability as the long term performance level of a process after it has been brought under statistical control. It is the ability to produce a product that will consistently meet the design requirement and customer expectation.

Common indicators used in capability analysis (C_p , C_{pu} , C_{pl} and C_{pk}) were considered in this study. They are defined in [11, 12]

The limit of capability chosen in this study is $C_{pk} \geq 1$. In this condition, a process is considered as capable and that means the process produces less than 2700 non conforming parts per million.

USL and LSL were determined from the ISO 8062 Standard [13]. Metal based additive manufacturing processes are also close to casting processes. It is therefore interesting to compute the capability from ISO 8062 Standard [13]. The capability obtained was compared to the values announced by ARCAM [3] :

- $\pm 0.13 \text{ mm}$ if $D < 30 \text{ mm}$
- $\pm 0.2 \text{ mm}$ if $D \geq 30 \text{ mm}$

Where,

D : Dimension of the part

By this method, it is possible to compare the EBM process with Casting processes in terms of dimensional quality.

Economic Analysis

A first approach for an economic analysis was carried out based on the results obtained on the dimensional characterization. This economic analysis is only based on the volume of material produce and the additional cost incurred and the number of rejected parts. The Monte Carlo method was used to simulate the production sample whose dimension follow the experimental dispersion. The produced parts are cylinder with nominal height of 103.25 mm and nominal diameter of 21.70 mm. For each class of tolerance, 1,000,000 parts were simulated to determine if the blank has sufficient allowance to be machined (otherwise the part is rejected). The systematic error has not been taken into account for the simulation.

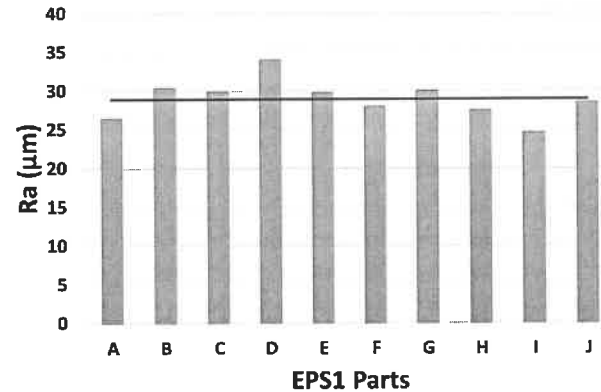


FIGURE 3. Surface Roughness (Ra value) measured on EPS1 (average value is the plain line on the diagram) [6]

The average cost is define as :

$$C_{av} = (p \cdot \rho \cdot V_{av}) \cdot \frac{1}{1 - \tau_r} \quad (1)$$

Where,

C_{av} : average Cost

p : powder price (160 €/kg)

ρ : density

τ_r : release rate

V_{av} : average volume of the produced samples

RESULTS

This section is divided in 4 steps : a surface characterization, a dimensional characterization, a capability analysis and an economic analysis.

Surface characterization

The surface characterization shows that the arithmetic roughness (Ra) obtained and the Ra announced by ARCAM [3] are quite similar. On figure 3 all the values are a bit larger than 25 μm excepted for sample I. All the results are summarized in Table 1. The average Ra value of the four EPS is given as well. This Table highlights that all the average values are larger than 25 μm . If we compare the Ra value with the Ra value obtained by casting process, EBM is near a sand casting process for the surface quality.

Dimensional characterization

The measurement of the samples shows that in the build direction (z axis), the average value is lower than the target value. The trend is opposite for the measure of the diameters for wich the

TABLE 1. A summary of the surface roughness (*Ra* value) measured for all the samples

Ra	Average Values (μm)
EPS 1	28.93
EPS 2	25.94
EPS 3	30.12
EPS 4	27.58

TABLE 2. Summary of the measures for all the samples

		Target value (mm)	Systematic error	σ
EPS 1	Height	103.250	-0.088	0.124
	cyl1	21.070	+0.087	0.104
	cyl2	9.656	+0.055	0.122
	cyl3	21.070	+0.008	0.067
EPS 2	Height	81.949	- 0.568	0.114
	cyl1	15.405	+ 0.060	0.055
	cyl2	7.059	+0.099	0.089
	cyl3	15.405	+0.037	0.068
EPS 3	Height	60.858	-0.502	0.075
	cyl1	11.999	+0.108	0.083
	cyl2	5.498	+0.017	0.024
	cyl3	11.999	+0.107	0.094
EPS 4	Height	54.934	-0.054	0.105
	cyl1	6.905	+0.031	0.059
	cyl2	3.165	+0.118	0.130
	cyl3	6.905	+0.016	0.081

average value is larger than the target value. It should be noted that the height measurements are made in the build direction (Z axis) and the diameter measurements are made in the XY direction.

Table 2 shows that a random error as well as a systematic error are found. The random error is related to the process but not the systematic one. The systematic error varies according to the axes considered (Z and XY directions). This error may depend on the calibration of the machine. Those very systematic small deviations are indeed most probably arising from different causes such as for instance imperfect table motor calibration for the Z direction. Once established, they can be suppressed by applying a dilatation factor to the CAD file (in the XY plan and another in the Z direction).

Capability analysis

In addition to the paper [6], a capability analysis from Standard ISO8062 [13] to compare the

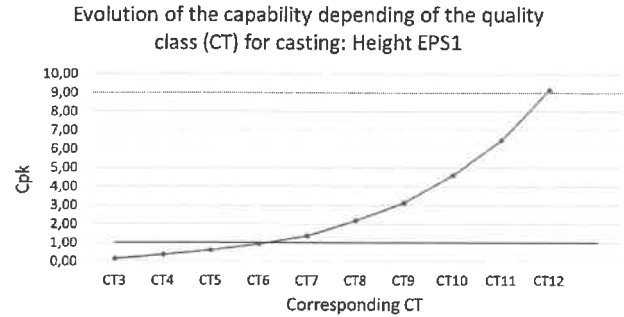


FIGURE 4. Capability analysis from ISO8062 Standard. CT7 is reached.

EBM process with casting processes. The capability analysis was conducted on EPS1 and EPS2 samples. Figure 4 shows the evolution of the capability with the class of quality for the diameter of the sample EPS1. The process capability is statistically guaranteed for a CT 7. The same results were observed for other samples and dimensions.

Economic analysis

The economic analysis was done with 2 machining allowances. The first case (blue on Figure 5) is for an addition of $\frac{CT}{2}$ on the nominal dimension of the sample. By this methodology, the Figure 5 highlight a minimum on the curvature (for a CT4). The minimum observed on this curve is explained by the fact that the percentage of release increase drastically with the diminution of the class of tolerances (see Figure 6). The second curve (in red on Figure 5) is for a machining allowance of $\frac{CT}{2} +$ a constant value of 0.3 mm (like in die casting). In this case, the curve has no minimum because the percentage of release is zero. That means all the produced parts respect the minimum dimension before the finishing process. So, it is sure that there is enough material all along the part.

This economic analysis can be further refined. Here a first step is presented but this approach will allow to define an ideal machining allowance.

CONCLUSIONS

The dimensional characterization of the samples shows that the error is composed of a random error and a systematic one. The random error is the error related to the EBM process. It is also noticed that the systematic error depends on the direction (XY direction and Z direction). With this systematic error, the IT class of the process is a CT7 (from ISO8062 casting standard) (see Figure 4). To improve it, the average value must be as close as possible to the target value. This difference

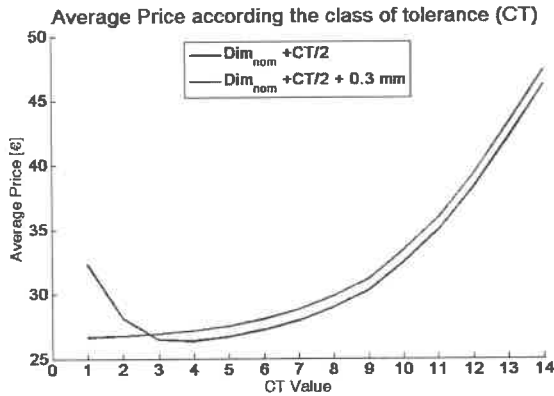


FIGURE 5. Average price according to the class of tolerance (CT)

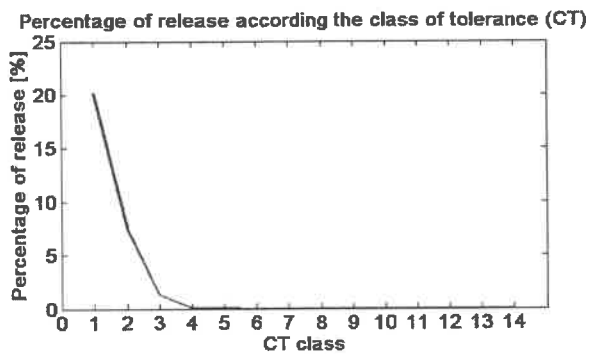


FIGURE 6. Percentage of release according to the class of tolerance (CT)

depends on the calibration of the machine. Assuming a perfect machine calibration would lower the CT to level 6 or even 5.

If we check in the Standard ISO 8062 [13] CT7 is a class of quality for light alloy by different processes:

- Automatic sand casting : $CT7 \rightarrow CT9$;
- Permanent and semi-permanent mould castings : $CT6 \rightarrow CT8$
- Die casting : $CT5 \rightarrow CT7$.

The analysis of our samples showed that the tolerances obtained by EBM are comparable to those obtained by die casting. The roughness of the part is similar to sand casting. It is therefore a good near net shape process.

The definition of the machining allowance is done by two ways. First, the recommendation for die casting ($0.3mm + \frac{1}{2}IT$) are follow and then only the $\frac{1}{2}IT$ was added. This analysis make it possible to perform an economic optimization of the process for blank production. Using a higher machining allowance reduces the rejection rate of parts (less risk of a dimension under minimal tolerance level) but increases the consumption of material.

A first economic analysis was carried out. This economic analysis is only based on the material cost. Which represents 20-30 percent of the total cost. This model can be improved by adding the preparation cost, the machine cost, the post treatment cost, etc. [14]. Such full economic model will also be geometry dependent where precise machining allowance is more critical for thin part with a high Surface/Volume ratio.

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LASER POLISHING OF ADDITIVE MANUFACTURED STEEL AND TITANIUM COMPONENTS

Bethan H. Smith¹, TianLong See¹, Florine Hiersemenzel¹, Khaled Kaja² and Mohammad Antar¹

¹The Manufacturing Technology Centre, Coventry, UK

²Bruker UK Limited, Coventry, UK

INTRODUCTION

Additive manufactured (AM) parts produce rough surfaces in the as-built state compared to conventional machining methods. However, current finishing technologies available on the market struggle with the complex features and curved surfaces that deliver the advantages for AM technology over the traditional methods. Therefore, the high as-built surface roughness is a significant barrier to uptake for AM technologies in a production environment, especially for high-value manufacturing industries such as aerospace or medical.

Lasers have been used within the manufacturing industry for processes such as engraving and cutting, but using lasers for polishing metallic AM parts is a relatively new concept (1). The benefit of using laser polishing is the ability to surface-finish rough and complex components not only in a time- and cost-efficient way, but also more accurately than ever before.

There are a number of published research papers showing good results for laser polishing of milled or machined surfaces (2) (3). Studies on selective laser melting (SLM) parts using NdYAG and CO₂ lasers have also been conducted (4). Lamikiz et al. studied the effect of laser polishing on hardness and microstructure of SLM parts using a CO₂ laser, showing a reduction of surface roughness by 80 % (5). Modelling of the melt pool dynamics to improve polishing of AM parts has been investigated by Marimuthu who concluded that a more dynamic melt pool leads to rougher surfaces (6). Rosa et al. studied laser power, feed rate, overlap and strategy impacts on the surface quality of stainless steel (316L) SLM parts (1). This paper found that argon flow is critical to prevent oxidation, and an increased number of passes improves both the surface roughness and microstructure of the part. Key differences between the microstructures of SLM built Ti-6Al-4V and 316L steel have also been found.

Mertens et al. found that the β phase cooling in Ti-6Al-4V gives a more elongated surface structure compared to 316L steel, which was more prone to defects caused by insufficient melting (7).

There appears to be a gap in the research on the effects of laser polishing SLM parts (using a number of materials) on surface roughness and waviness. This paper aims to cover a small aspect of this gap.

In general, the literature recommends the use of pulsed lasers for micro-polishing, and continuous wavelength lasers for macro-polishing (8). Typically within the aerospace industry, a surface roughness profile arithmetic mean (R_a) of below 0.8 μm is suitable for the majority of applications (9). Continuous-wave (CW) laser polishing does, however, create undesirable surface waviness, despite reducing surface roughness significantly (10). Both, the surface roughness and waviness, are key parameters for assessing various laser polishing settings, with the aim to find the ideal setting for a given material.

This paper demonstrates laser polishing on AM stainless steel and titanium components through the SLM build technique. The effect of laser parameters (power and hatch distance) on surface topography and melted layer depth is presented here.

MATERIALS AND METHODS

Two types of materials are investigated: stainless steel of grade 316L and titanium alloy of grade Ti-6Al-4V. The AM components were manufactured using a SLM125HL model laser-based machine with the settings summarized in Table 1.

TABLE 1. AM build settings

Parameter (unit)	Ti64	316L
Layer thickness (μm)	30	30
Laser power (W)	175	175
Hatch distance (μm)	100	120

For the laser polishing, an IPG CW YLS-2000 fiber laser was used, which has a wavelength of 1070 nm and a maximum power output of 2 kW. The laser beam passed through a Raylase SS-II-HS-LD-30 scanning head and through a feed fiber of size 200 μm , resulting in a 400 μm diameter spot size. The AM components were placed in an argon gas filled chamber (flow rate 10m³/s) where a 5 mm x 5 mm area was polished. The set-up is shown in Figure 1.



FIGURE 1. Image showing experimental set-up

The effect of the laser's hatch distance (5 μm – 200 μm) and power (100 W – 450 W) on the surface finish quality was investigated using a number of instruments: the surface topography was visually assessed using a Hitachi TM3000 tabletop scanning electron microscope (SEM) and a Zeiss Axio Imager optical microscope. The surface topography was measured using a Bruker Contour GTK Elite optical white light interferometer.

RESULTS

Visual Surface Topography

The SEM images of the as-built and laser polished surfaces with different laser powers and hatch distances for 316L steel and Ti-6Al-4V titanium are shown in Figure 2 and Figure 3, respectively. Un-melted metal powder from the AM build in the form of spherical particles on the as-built surface can be clearly seen in Figure 2(a) and Figure 3(a), which is the main contribution to the rough surface finish of AM components. When the surface is irradiated with a low power laser beam (100 W) at a fixed hatch distance of 40 μm , these un-melted metal powder particles are partially melted (Figure 2(b) and Figure 3(b)). As the laser power increases

to 450 W, the un-melted metal powder becomes fully melted forming a smooth surface, (Figure 2(c), Figure 3(c)), with a formation of surface nanostructures, which can be observed at high magnification (1000 x).

At the fixed laser power of 250 W with changing hatch distances, the un-melted metal powder from the as-built surface was fully melted forming a smooth surface. Formation of nanostructures can be seen on the 316L stainless steel component (Figure 2(d)) but not on the Ti-6Al-4V titanium component (Figure 3(d,e)). As the hatch distance increases, the laser polished track can also be clearly seen on the 316L stainless steel component (Figure 2(e)) but this is not observed on the Ti-6Al-4V titanium component (Figure 3(e)).

Dark spots are visible on some of the polished surfaces (Figure 2(c), 2(e) and Figure 3(c), (d),(e)). These are believed to be formed during the AM build process as they are also present in the as-built surfaces (Figure 2(a) and Figure 3(a)). Platelet shaped features are also observed on polished Ti-6Al-4V surfaces (Figure 3(d), (e)).

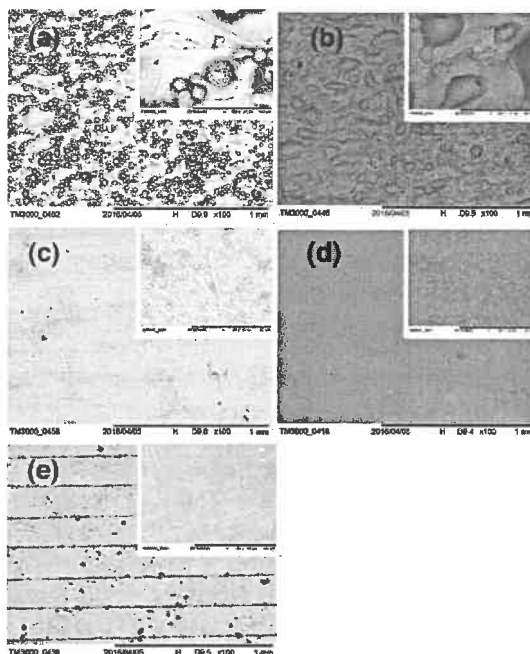


FIGURE 2. SEM images of (a) as-built, laser polished with (b) 100 W, 40 μm hatch distance, (c) 450 W, 40 μm hatch distance, (d) 250 W, 5 μm hatch distance and (e) 250 W, 200 μm hatch distance on 316L steel surface

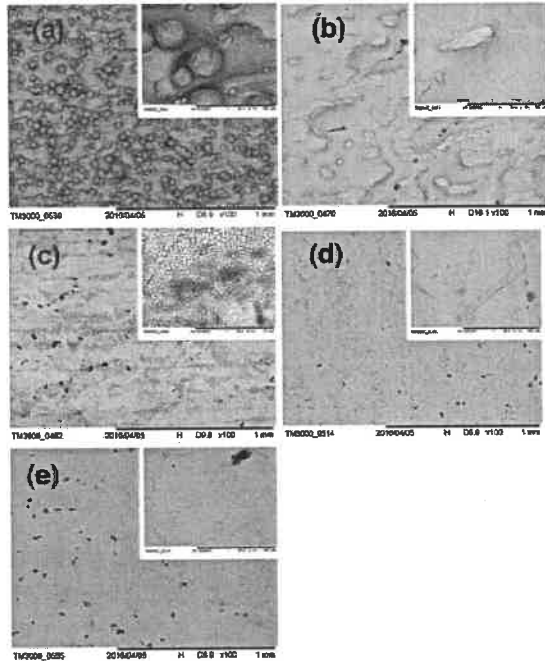


FIGURE 3. SEM images of (a) as-built, laser polished with (b) 100 W, 40 μm hatch distance, (c) 450 W, 40 μm hatch distance, (d) 250 W, 5 μm hatch distance and (e) 250 W, 200 μm hatch distance on Ti-6Al-4V titanium surface.

Surface Topography Analysis Fundamentals and definitions

A manufactured surface constitutes of a range of surfaces frequencies. The high frequencies of the surface are generally classed as the roughness, the medium frequencies are classed as the waviness and the low frequency are responsible for the surface's form. Here, the surface roughness and waviness are characterized as the arithmetic mean, using the respective frequency ranges. A parameter called the waviness cut-off (λ_c , the frequency being reciprocal to the wavelength) is used to define the boundary between the roughness and the waviness. This boundary value is specific to each surface. The impact of choosing an unsuitable λ_c can be significant and is one of the challenges faced in the manufacturing industry and is of a growing concern (11)(12). The symbol for the surface arithmetic mean is S_a , however, here there is a necessity to distinguish between S_a for roughness and S_a for waviness, so these will be noted as S_{a_r} and S_{a_w} in this paper.

In order to find the appropriate λ_c value, the surface of a laser polished area is measured using the white light interferometer with a sample field of view of 1.7mm $\times$ 1.5 mm and the raw data is filtered using a range of λ_c as shown in Figure 4.

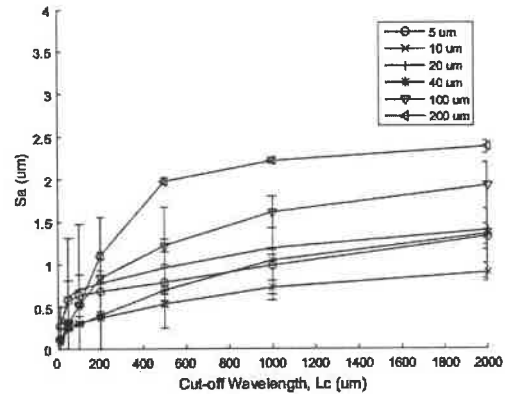


FIGURE 4: Surface roughness, S_{a_r} measurement values for different λ_c filters for the Ti-6Al-4V polished component with different hatch distances.

The effect of λ_c on S_{a_r} can clearly be seen in Figure 3. By observing where the S_{a_r} value begins to plateau, a suitable λ_c can be identified for each polished area to separate the roughness from the waviness.

Effect of Hatch Distance

The S_{a_r} and S_{a_w} value plot for polished 316L steel and Ti-6Al-4V titanium for varying hatch distance at constant power of 250W is shown in Figure 5. From Figure 5(a), it can be observed that both S_{a_r} and S_{a_w} of the polished 316L steel surface decrease with increasing hatch distance until it achieves an asymptotical value at approximately 20 μm hatch distance for S_{a_r} and approximately 40 μm hatch distance for S_{a_w} . As for Ti-6Al-4V titanium, both S_{a_r} and S_{a_w} values increase with increasing hatch distance as shown in Figure 5(b).

From Figure 5, the optimum hatch distance for laser polishing at a constant laser power of 250 W for 316L steel was 40 μm , achieving an S_{a_r} value of 0.4 μm and S_{a_w} value of 1.5 μm . As for Ti-6Al-4V titanium, the optimum hatch distance was 10 μm , achieving an S_{a_r} value of 0.4 μm and S_{a_w} value of 0.5 μm .

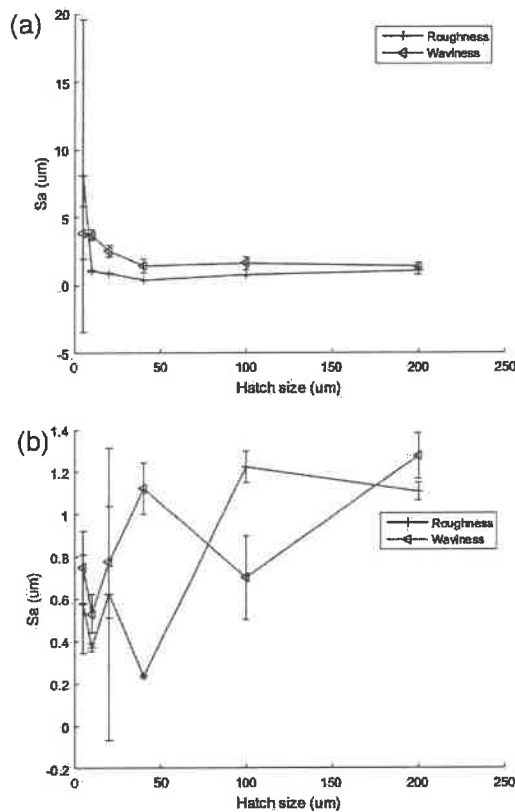


FIGURE 5. Graphs showing Sa_r and Sa_w versus hatch size at constant laser power of 250 W for polished (a) 316L steel and (b) Ti-6Al-4V

Effect of Laser Power

The graphs showing Sa_r and Sa_w against laser power at constant hatch distance of 40 μm for polished 316L steel and Ti-6Al-4V titanium are found in Figure 6. From Figure 6(a), it can be observed that the Sa_r value for polished 316L steel decreases with laser power at the low power region (< 250 W) but increases thereafter, whereas the Sa_w value remains approximately constant with increasing laser power. As for Ti-6Al-4V titanium, the Sa_r value decreases with increasing laser power and achieves an asymptotical value at 250 W, whereas the Sa_w value increases with laser power till 150 W and then decreases with laser power as shown in Figure 6(b).

As shown in Figure 6 the optimum laser power for laser polishing at a constant hatch distance of 40 μm for 316L steel was found to be 250 W with an Sa_r value of 0.4 μm and Sa_w value of 1.5 μm . For Ti-6Al-4V titanium, the optimum laser power was found to be 450 W with an Sa_r value of 0.3 μm and Sa_w value of 0.7 μm .

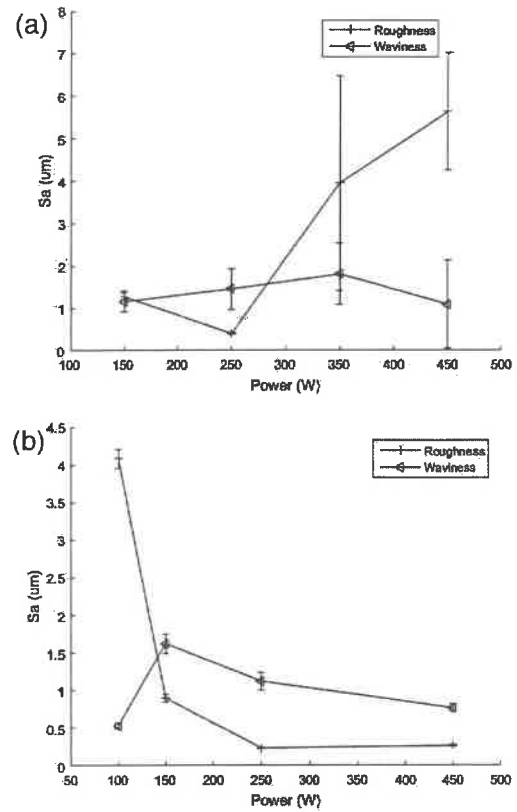


FIGURE 6. Graphs showing Sa_r and Sa_w versus laser power at constant hatch size of 40 μm for polished (a) 316L steel and (b) Ti-6Al-4V.

Re-melted layer

The melted layer depth of the laser polished area is examined through cross-sectioning the samples which are polished and etched. The two materials had different micro-structures and so the melted layers were also dissimilar. In Figure 7 it can be seen that the Ti-6Al-4V titanium re-melted layer is deeper (400 μm) as compared to 316L steel (50 μm). The thickness of the re-melted layers for 316L steel appear consistently uniform across the polished area with only a 50-100 μm edge area of changing gradient. On the contrary, the thickness of the re-melted layer for Ti-6Al-4V titanium is not uniform across the polished area with a thicker melted layer at the middle of the polished area forming a bowl like shape.

The change in re-melted layer thickness with hatch distance and laser power is shown in Figure 8. The re-melted layer thickness for 316L steel remains relatively constant with increasing hatch distance at constant laser power of 250 W; whereas a sharp increase in thickness for Ti-6Al-4V titanium at low hatch distance (< 40 μm)

can be observed (Figure 8(a)). The re-melted layer thickness increases with laser power at constant hatch distance of 40 μm for both 316L steel and Ti-6Al-4V titanium as shown in Figure 8(b).

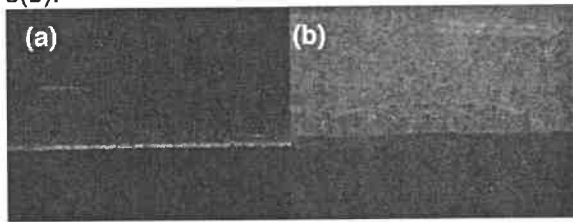


FIGURE 7 Cross-sectional optical images of re-melted layers for a) 316L steel at 250 W and 40 μm hatch distance and b) Ti-6Al-4V titanium at 250 W and 40 μm hatch distance

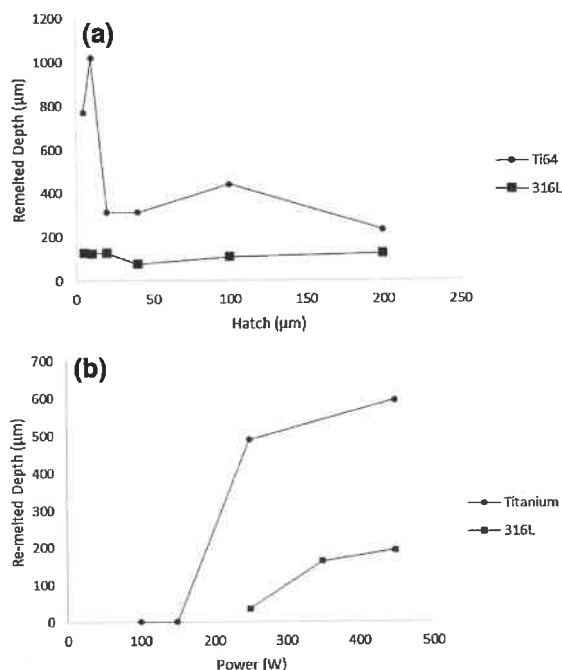


FIGURE 8 Graphs showing re-melted layer depth versus a) hatch size and b) laser power for both 316L steel and Ti-6Al-4V titanium

DISCUSSION

The variation in surface roughness clearly indicates the influence of material properties on laser parameter selection for achieving optimum polishing quality (lowest roughness and waviness). Power density increases with reducing hatch distance, and reduces as the hatch distance increases. From Figure 5(a), it is observed that 316L steel required lower power density per unit area as the roughness and waviness value decrease with increasing hatch distance. On the contrary, as shown in Figure 5(b), Ti-6Al-4V titanium required higher power

density per unit area as the roughness and waviness increases with hatch distance. The reduction in surface quality with increasing hatch distance for Ti-6Al-4V titanium is due to the power density being too low to create a melt pool of sufficient velocity needed to create a smoother surface (6). Figure 6 supports the above observation where the lower roughness and waviness is seen for 316L steel components when polished with lower power. In contrast, a higher power is required for Ti-6Al-4V titanium to achieve lower roughness and waviness. The reduction in surface quality for 316L steel with increasing power (shown in Figure 6(a)) is due to the high melt pool velocity created through over melting of the surface - resulting in a rougher surface (6). This is also supported by the observed difference in re-melted layers (Figure 7). The bowl-like shape of the Ti-6Al-4V melted layer indicates the affected melted areas is much larger and less uniform as compared to 316L steel which showed a more uniform and thinner melted layer even at low power (150W).

Such observation can be explained through the difference in material properties between 316L steel and Ti-6Al-4V titanium. 316L steel has a thermal conductivity of $\sim 14 \text{ W/m-K}$, heat capacity of $0.5 \text{ J/g}^\circ\text{C}$ and a melting temperature of 1380°C . On the other hand, Ti-6Al-4V titanium has a thermal conductivity of $\sim 7.8 \text{ W/m-K}$, heat capacity of $0.56 \text{ J/g}^\circ\text{C}$ and melting temperature of 1650°C (13) (14). Although the two materials have similar heat capacity, 316L steel has a lower melting temperature as compared to Ti-6Al-4V titanium. Furthermore, the rate of increase in heat capacity with temperature for 316L steel is lower than Ti-6Al-4V (14). Therefore, 316L steel required a much lower power density to achieve re-melting for polishing.

The re-melted layer thickness is influenced by the thermal conductivity of the material. As 316L steel has a much higher thermal conductivity than Ti-6Al-4V, a smaller thermal gradient is expected around the polished area - since heat dissipation rate is higher with higher thermal conductivity (7) (15) (16). Furthermore, the thermal conductivity of both materials increases with temperature and since 316L steel has a lower melting temperature and lower heat capacity at higher temperature, the rate of increase in thermal conductivity for 316L steel is higher as compared to Ti-6Al-4V. Hence all the polished surfaces for 316L steel exhibit a

uniform melted layer across the polished region. In comparison Ti-6Al-4V titanium exhibits a non-uniform melted area with a thicker melt depth in the middle of the polished region as the heat is not dissipated as efficiently.

CONCLUSIONS

The paper presented the capability of laser polishing on 316L steel and Ti-6Al-4V titanium SLM build AM components. The conclusions from the investigation are summarized as follows:

- Both roughness and waviness are key parameters when assessing laser polished parts;
- The optimum hatch distance and power parameters vary between materials;
- An optimum surface roughness and waviness (S_a) of $0.3\ \mu\text{m}$ and $1.5\ \mu\text{m}$, respectively, for 316L steel, and $0.4\ \mu\text{m}$ and $0.7\ \mu\text{m}$, respectively, for Ti-6Al-4V titanium can be achieved;
- For 316L steel a hatch distance of $40\ \mu\text{m}$ and 250 W power was found to give optimum improvement to the surface;
- For Ti-6Al-4V titanium an optimum hatch distance of $10\ \mu\text{m}$ and a power of 450 W gave optimal improvement to the surface;
- The depth and shape of the re-melted layer was unique for each material;
- Ti-6Al-4V titanium had deeper (four fold) and less uniform melted layer compared to 316L steel;
- The re-melted layer increased in depth for reducing hatch distance and increasing power for both materials.

FUTURE WORK

Using the results of this investigation, additional optimisation of laser polishing parameters is required to further reduce the surface roughness and waviness of the polished surface. More data would allow observations in this paper to be fully defined, such as the surface roughness and waviness correlations with power density. Further investigation into the effect of this type of polishing on the fatigue and tensile strength of the part would also help strengthen the data for using laser polishing within additive manufacturing.

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Integrating Metal AM with Milling and Non-Traditional Machining to Improve Surface Properties

A. S. Iquebal¹, S. Shrestha², Z. Wang¹, GP. Manogharan² and S. Bukkapatnam^{*1}

¹ Department of Industrial and Systems Engineering, Texas A&M University,
College Station, TX.

² Department of Mechanical and Industrial Engineering, Youngstown State University,
Youngstown, OH.

INTRODUCTION

Metal Additive Manufacturing (AM) market has grown by over 45% in the past year, and the process is emerging as a desirable option for fabricating freeform, custom components with optimized topology [1] for the biomedical and aerospace industry. However, with growing range of alloys that can be fabricated with this process, there is a significant need to address two specific challenges that impede broader commercial viability of AM processes, namely, surface finish and part feature tolerances. Most mechanical and aerospace applications require "mirror" surface finish ($R_a < 50$ nm) with tighter part feature tolerance (dimensional tolerance of ± 10 μ m). Thus there exists a need to focus on post processing technologies. Moreover, custom surface requirements, e.g., differential surface finish in biomedical components is of utmost importance. For example, for biomedical implants [2] a roughness R_a of $0.5 - 8.5$ μ m is considered to be most conducive for osseointegration while ultra-smooth finish ($R_a < 0.1$ μ m) is necessary on the bearing surfaces (e.g. at hip and knee joints) to ensure performance as well as durability under dynamic loading [3].

Traditional subtractive methods offer advantages that might be able to mitigate these challenges. However, traditional methods suffer from poor material utilization, challenges in machinability of superalloys, limited part complexity, custom tooling requirement for every part design, etc. Therefore, integrating AM with subtractive methods, such as machining, grinding and polishing through a hybrid approach is desirable. It is imperative to develop post-processing strategies that are independent of preceding AM process and/or material. Recently published work has reviewed hybrid processes and has classified them based on the principle of integration [4][5]. Much of the work in

this area has focused on directed energy metal deposition processes such as wire welding using metal inert gas, metal active gas and laser melting due to the relative ease of integration. There are only limited efforts on the post-processing of Electron Beam Melting (EBM) components, a powder bed fusion metal AM systems. In particular EBM offers the processing speeds and scale-up capabilities that the biomedical implant industry considers very attractive. However the joint effect of EBM printing under various processing conditions followed by post-processing with machining and polishing under varying conditions—so important for industrial translation of the AM process— has not received much attention thus far.

Towards addressing this gap we report one of the first longitudinal studies of Ti-6Al-4V subjected to EBM printing from their powder precursors, followed by a series of machining and fine-abrasive finishing processes. Our study is aimed at gathering understandings of the impact of various processing conditions on the surface morphology.

LITERATURE REVIEW

Metal AM processes, including EBM have been increasingly accepted as the most desirable means to fabricate custom biomedical and aerospace components. However, the surface quality of AM components is poor and poses a great challenge for its applicability in bearing applications, e.g., biomedical implants. Hence post processing methods are considered as a crucial yet challenging step in the AM practice, and it is emerging as one of the critical elements of hybrid manufacturing systems. Moreover, economical post processing technologies with minimal scrap rates is necessary to realize the desired surface characteristics. However, only a handful of efforts have been reported in the

literature on the finishing of EBM printed components [6].

One of most common approaches to improve surface quality and reduce porosity is through solid state sintering or densification process [7]. High temperatures (e.g., 1300° C) in β phase are normally selected for the sintering, well below the melting point. It involves reduction in the surface area and surface free energy via diffusional flow of composing elements, surface diffusion, grain boundary diffusion and lattice diffusion. Hot Isostatic Pressing (HIP) [7, 8] process is also widely adopted since the required temperature is around 900° C which is relatively lower than sintering. Although sintering and "HIPing" are effective in reducing the surface voids, no significant improvement in the Young's modulus and microhardness has been reported [9] and it often increases the bulk density which might not be recommended in many aerospace applications. Sandblasting is another widely adopted method [10]. Here a stream of sand is shot against the workpiece to minimize the surface irregularities or remove other undesirable particles. Sandblasting is only effective in controlling the initial surface roughness, but it cannot be used to achieve a mirror finish. Shot peening [11] is a relatively efficient method for inducing compressive stress and enhance the mechanical properties in the workpiece while reducing the surface roughness, but it results in the deterioration of the fatigue strength due to initiation of crack from internal pores during peening. Another class of post-processing method are based on using additives such as TiH_2 to the starting powder [12] or *in-situ* addition of elements such as Boron [13]. While the additives may significantly improve the mechanical properties, the purity of the starting material may be lost and might not be desirable in many biomedical applications. Recent studies [6] has reported the influence of different post-processing strategies such as machining and polishing on the surface characteristics and microhardness of EBM fabricated Ti6Al4V samples.

To investigate and thence optimize the surface characteristics and mechanical properties, we propose a longitudinal post-processing strategy based on integrating machining to improve the mechanical properties followed by fine-abrasive finishing to impart a mirror finish to the workpiece.

EXPERIMENTAL APPROACH

Six cylindrical Ti-6Al-4V disks of dimension $\phi 50.8\text{mm} \times 15\text{mm}$ were printed using an ARCAM EBM system operating at a vacuum below 2×10^{-2} mbar, acceleration voltage of 60 kV with 50 μm layer thickness. The raked layer was first preheated to $\sim 650^\circ\text{C}$ by the scanning electron beam at a scan speed of $\sim 10^4$ mm/s in multiple scans at $\sim 30\text{mA}$. The Three of the samples were printed along the x direction relative to the AM build plate and the other three along the z-direction. The effects of post-processing that consisted of machining followed by fine-abrasive polishing, on the surface characteristics each one of these samples was studied. Machining parameters selected based on Machinery's Handbook were 1 mm depth of cut, spindle speed of 1250 rpm and 250 mm/min feed rate under for dry milling condition. Subsequently, the machined samples were subjected to a step wise polishing process. First, the milled EBM Ti-6Al-4V workpieces were subjected to surface grinding using 320 grit SiC abrasives to flatten the chatter marks and deep scratches. Next, a fine abrasive finishing process was performed on a Buehler Metaserv Grinder-Polisher (model 95-C2348-160) to progressively polish the surface to reduce the roughness to $< 100\text{ nm}$ range. Each step involved the application of polishing pads of increasing grit size. Finally, 0.05 μm alumina aqueous suspension (20% by wt.) with $\text{pH} \approx 7.5$ was used on a micro cloth to give the final surface finish for 20 minutes. The lapping process here promotes a 3-body abrasion mechanism as opposed to a 2-body abrasion mechanism (while using polishing pads), which prevents the deep cuts into the work piece.

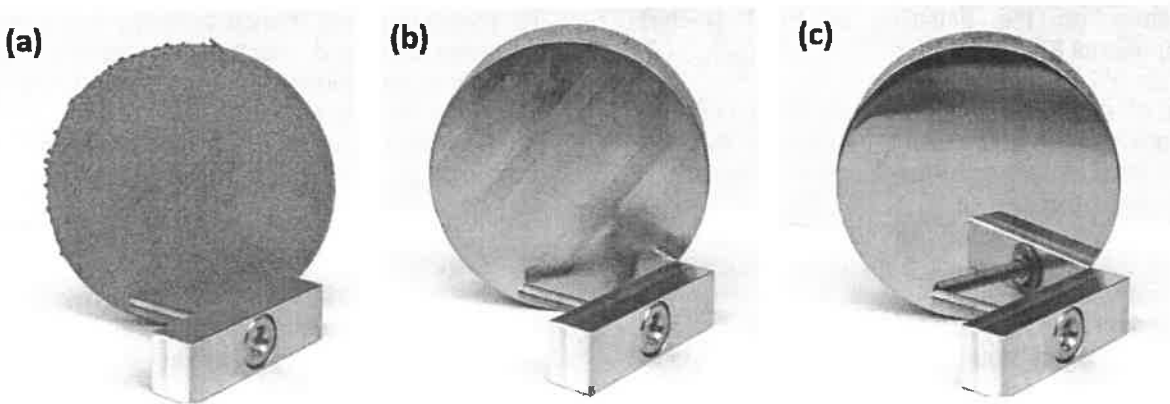


FIGURE 1. Representative Ti-6Al-4V surfaces for the (a) as-EBM fabricated ($R_a \sim 25 \mu\text{m}$) (b) after dry machining ($R_a \sim 0.575 \mu\text{m}$) and (c) after fine abrasive finishing ($R_a \sim 0.04 \mu\text{m}$)

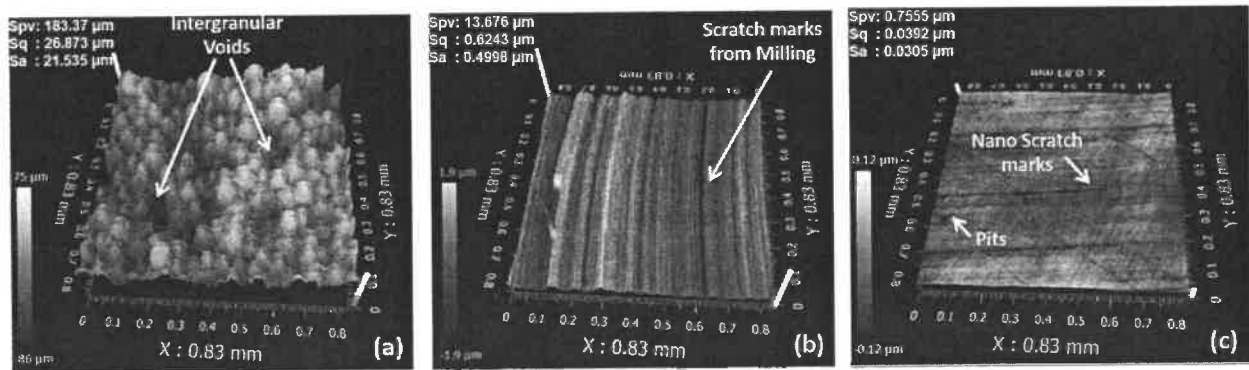


FIGURE 2. Transformation of the surface morphology due to fine abrasive finishing captured using Zegage. (a) before fine abrasive finishing showing a predominant granular structure with intergranular voids and (b) milled surface shows the tool marks, significant chatter marks as well as deep scratches (c) significant reduction in voids after the multistep finishing process with reduction especially in S_{pv} by nearly two orders of magnitude.

However, due to agglomeration of abrasive particles that form larger abrasives clusters sometimes results in micro- and nano-scratch marks. Therefore, the aqueous alumina suspension was continuously flushed while polishing to introduce fresh abrasive particles to mitigate the scratch that could build up due to the used up abrasive particles.

The polished surface was analyzed under a white light interferometer (Zegage from Zygo) to measure the average surface roughness (S_a) and peak to valley distance (S_{pv}). Micro hardness testing was also performed on the sample in a Nanovea M1 test platform using a Berkovich indenter to understand sub-surface mechanical properties.

RESULTS

Surface profiles captured using the white light interferometer are shown in Figures 2(a, b & c). The figures capture the surface morphology evolution of the as-printed state from the EBM process through post-processing with machining and polishing. It should be noted that the granular structure shown in Figure 2(a) exhibit voids in the work piece resulting in a much lower surface density. The machined surface (Fig. 2(b)); however has a lower surface roughness ($\sim 0.50 \mu\text{m}$) but significant feed marks (with deep tool signature) along with a possible low-amplitude chatter marks could be observed. On the other hand, polished work piece is completely devoid of any granular structure, inter-granular voids as well as the chatter marks, although it shows signs of scratch marks and pits on the surface as depicted in Fig. 2(c). The

scratch marks may be attributed to the limitations of mechanical polishing on the finishing setup as well as possible agglomeration of abrasives forming larger abrasive particles when an aqueous solution is employed. Additionally, the preliminary results of micro-hardness testing on machined as well as the polished surface showed an average improvement in hardness value (HV) of 37% (dry milling) when compared to as-EBM printed samples.

In order to account for the reduction in surface porosity, we calculated the proportion of voids on the surface using the image processing and analysis software, ImageJ v1.8.0_77. Using the surface profiles collected in Zygo, we set the threshold limit for the pixel values representing voids. As shown in Fig. 3, the voids are represented by the black region on the surface. We can easily notice the inter-particle voids on

the as-EBM sample (Fig. 2(a) & 3(a)) and the particle boundaries. Since the surface is mostly occupied by voids, the fraction of bearing area is only 45%. Machining do result in an increase in the hardness, it only increases the percentage area to 62% (Fig. 3(b)). This is mostly due to chatter marks during machining which leaves behind deep scratch marks and an irregular profile in the orthogonal direction. Fluid abrasive however, results a significant reduction in the surface porosity and increases the %area to almost 99.9% (Fig. 3(c)). These results indicate the specific advantages of employing traditional machining and/or abrasive fluid based finishing to: (1) improve the overall surface roughness, (2) improve bearing ratio and (3) improve microhardness compared to the as-EBM fabricated samples.

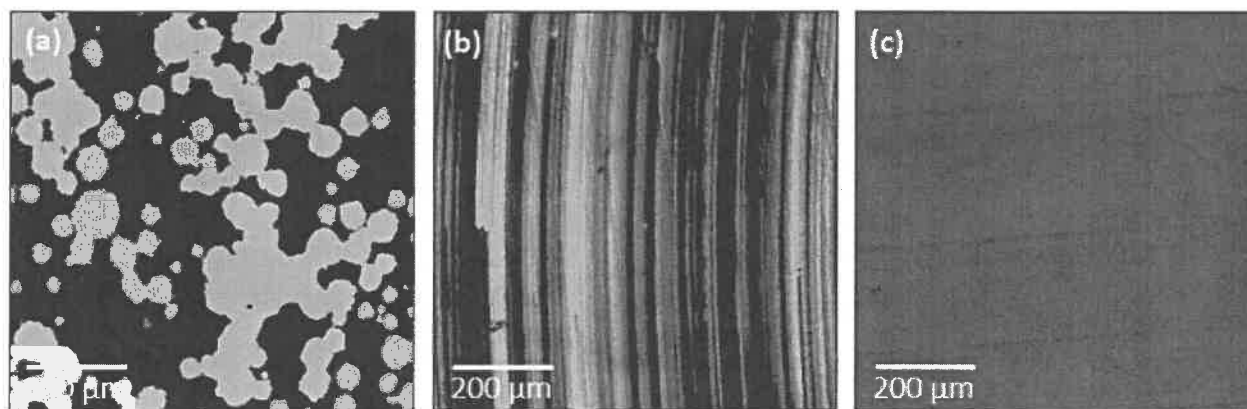


FIGURE 3. Threshold micrographs obtained from ImageJ for (a) as-EBM (b) machined and (c) fine abrasive fluid polishing with voids represented by the black region.

CONCLUSIONS

This research has presented one of first longitudinal studies on the effects of post-processing of metal AM fabricated parts (Ti-6Al-4V EBM) via a machining followed by a carefully crafted multi-step fine-abrasive finishing process. Surface characteristics observed from the white light interferometry as well micro-hardness testing suggests that the average surface roughness improved by 98.1% (to $S_a < 40\text{nm}$) and increased surface hardness by almost 35% ($VHN \approx 450$). Surface porosity measurements revealed that there was a significant increase in the fraction of bearing area to almost 99.9% after fine abrasive

polishing compared to the as-EBM sample, thus providing an effective means to enhance the bearing capacity of AM components. This study showed the importance of longitudinal post-processing by integrating machining with multi-step fine abrasive finishing. Future work will be focused towards developing a complete experimental design to assess the effect of machining and polishing parameters on the surface characteristics and mechanical properties after post processing.

ACKNOWLEDGMENT

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‘ADDITIVE IS NOT AN ISLAND’ – A RENISHAW SOLUTION APPROACH TO THE CONTROL OF AM PART QUALITY.

Michael J. McClelland (MEng)

Group Software

Renishaw plc

Wotton-under-Edge, Gloucestershire, United Kingdom

INTRODUCTION

With the hype of additive manufacturing (AM) gradually wearing off, undoubtedly there comes disappointment for anyone who believed it could operate as a monolithic standalone solution. As the technology leaves the labs and enters factory floors with the average number of machines in a facility moving from one, to tens; it should be intrinsically clear that complimentary tools are needed. ‘Additive is not an island’. Only when experienced engineers utilise AM as a link within a technology chain can there be any chance of accurate parts of the required quality coming off the end of the production line.

The key to Renishaw’s approach is to provide not only the equipment needed to build AM parts, but the end to end system required to provide a validated solution to users at each stage of manufacturing.

1. BUILD PREPARATION
2. PART MANUFACTURE
3. GAUGING
4. FINISHING OPERATIONS
5. CO-ORDINATE MEASUREMENT



FIGURE 1. The Renishaw ‘Solution Approach’.

BUILD PREPARATION

For Renishaw, this begins with the build preparation software. QuantAM™ enables users to develop material files, orient and support parts, layout builds, review toolpaths and export machine files to Renishaw’s AM systems.

QuantAM exemplifies Renishaw’s view on open access. Within the software, users have access to essentially all of the parameters that will affect the quality and accuracy of their parts. Material

parameter files are completely open and may be viewed and modified as necessary. This openness is key to ensuring accuracy as users may develop specific parameters to achieve the finest possible surface finish on specific materials or highly customise parameters for a specific part geometry or manufacturing run.

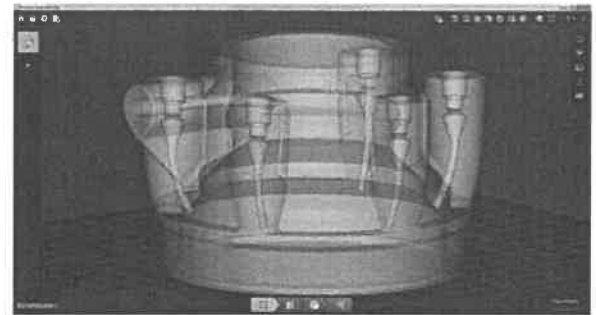


FIGURE 2. QuantAM Build Preparation Software.

Within the software, test coupons may be defined and arrayed as necessary. Material parameters for these coupons are then displayed in a defined.csv file format in which the user can edit the parameters to produce an array of differing combinations based on experimental design methodologies.

After editing the toolpath and energy parameters, the customised samples may be built and empirically tested to determine which parameter set produces the optimal results for form, fit, surface finish and mechanical properties.

The Renishaw AM system utilises a point exposure method meaning it fires the laser at a specific point for a set period before stopping and moving a set distance to the next point and firing again. Point scanning in this manner has been shown to increase the achievable feature resolution in AM components.

Table 1 shows how surface finish can be influenced by varying the exposure time at each point (Exp) and the distance between successive

exposures (PD) using the QuantAM material development tools.

TABLE 1. Excerpt of empirical surface finish results from QuantAM material development

Part	PD	Exp	Ra	Rz
...	...	...	...	...
8	70	90	7.68	42.16
9	80	90	8.83	47.13
10	90	90	7.59	44.44
11	50	100	4.38	26.71
12	60	100	5.14	30.69
13	70	100	6.83	32.07
...	...	...	...	...

QuantAM also enables Renishaw to bring many other key improvements in AM toolpath strategies, one of which is termed 'intermittent point scanning'. In this strategy, rather than scanning the points sequentially, it is possible to produce path planning that will individually expose laser points in sequences designed to inhibit grain growth and to reduce stress and micro-cracking in materials that are difficult to weld.

Helical grain growth caused by successive border scans has also been cited as a contributor to fatigue failure [1]. Through variation of the direction of scan on consecutive contours and alteration of the border scan direction on every layer QuantAM has made it possible to reduce the development of helical surface grains.

'Bridging distortions' are another well-known issue in AM. They result when two separate part contours meet and form a bridging layer.

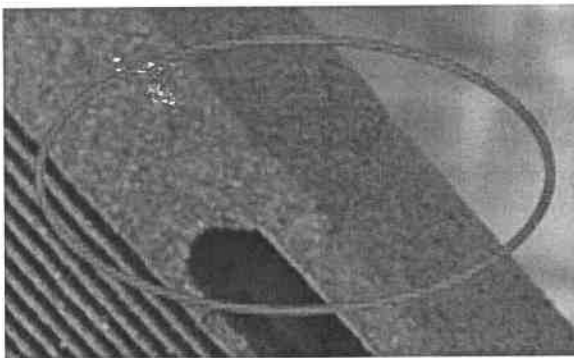


FIGURE 3. Bridging distortion in an AM part

As the layer cools, the shrinkage caused by the increase in surface area triggers localised distortion of the layer and preceding geometry.

Traditionally the bridging layer would be scanned in one pass but in QuantAM the layer is split into three regions, two large regions that account for the majority of the cross sectional area and a small bridging region. The two large unconnected regions are scanned first and allowed to cool and shrink. The small bridging region then joins the two and as the area is relatively small, the shrinkage produced has a negligible effect on part form.

Coupling these improved scanning strategies with border variation and intermittent point scanning, Renishaw aim to produce significant improvements in the fatigue characteristics, resolution and accuracy of AM parts.

PART MANUFACTURE

The RenAM500M additive manufacturing system is indicative of Renishaw's philosophy of ensuring quality through ownership of all aspects of the product.

It also exhibits features such as Renishaw's nanometre accuracy-range Resolute™ linear encoders on mechanical assemblies giving $\leq \pm 1 \mu\text{m}$ linear positioning accuracy on Z-axis movements.

The in-house design, manufacture and assembly of the fusion optical module enables Renishaw to have an extremely tight grip on the specification and scanning performance of the system.

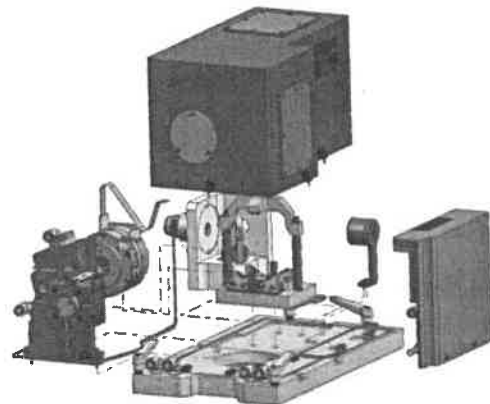


FIGURE 4. Fusion optical module

The internally developed and manufactured voice coil (focusing optic) can maintain dynamic focus

across the bed within one Rayleigh length whilst scanning at a speed of 4 m/s, negating the need for a flat field f-theta lens and ensuring that part accuracy remains within defined tolerances across the bed.

Ownership of the embedded control system software has also enabled Renishaw to highly optimise communications between controllers and optical components, increasing the positional accuracy and speed of scanning.

GAUGING

Once parts have been manufactured on the AM system, the first stage in the inspection process takes place. Equator™ is a non-Cartesian digital gauge. It is a low cost system that is unaffected by thermal variations in the production environment and can therefore be located directly on the production line rather than being housed in a temperature controlled CMM lab. The Equator gauging system enables the production team to programme pass/fail criteria based on a 'gold standard' AM build.



FIGURE 5. Equator Digital Gauge

The gold standard part is built and fully validated using a CMM. The gauge is then used to compare every part that comes off the AM production line to that gold standard. The digital gauge can be easily reprogrammed if the design changes which is ideal for additive parts where design iteration is common.

As an indication of capability, on a machined part, the system is able to control a 3mm diameter bore to $\pm 3 \mu\text{m}$. For an AM part, the tolerances are significantly higher than this meaning that in a

100% inspection environment, the system can quickly and cost effectively give a very reliable go/no go phase gate to indicate whether the build has produced the expected geometrical accuracy.

This means that a quick determination can be made on whether the part is within the required tolerance before continuing with what may be time consuming and expensive post process operations.

FINISHING OPERATIONS

Achievable AM surface finishes are generally in the 3-5 μm RA range for upskins and sidewalls and 5-15 μm RA on downskins and shallow inclines. Whilst sub 20 μm part tolerances are achievable for relatively simple geometries, tolerances in most real world applications are generally between 50 μm and 150 μm dependant on part geometry and surface orientation.

As a result, in almost all industrial AM applications, subtractive operations of some description will be required whether that entails reaming of high tolerance bores, thread cutting or surface milling.

On-machine probing systems such as Renishaw's Sprint™ probe can be used in a variety of operations, first and foremost to locate the net shape AM part in the machine tool where the geometrical freedom offered by AM can make datum recognition difficult.



FIGURE 6. Sprint - On machine probing system

Once the probing cycle has been completed, NC-Perfect Part™ can be used to perform part alignment. Perfect Part compares the measured points to the nominal geometry file. It then performs any translation and rotation operations needed to best-fit the subtractive machining toolpath definitions to the actual AM part. This means that small local or global distortions in the

AM part can be compensated for provided there is enough stock material on the part.

In the more challenging machining cases where hard metals, trapped powder and intermittent support cutting pose significant problems, in-process probing can also be used to measure tool wear and compensate cutter offsets or detect chipped tools before irreparable (and potentially very costly) damage is incurred on the AM component.

CO-ORDINATE MEASUREMENT

The last step in the quality chain is generally CMM inspection and this is where the REVO™ system is utilised. REVO can be mounted on a range of OEM CMMs, transforming them from 3 axis to synchronised 5 axis measurement tools. When in use, the CMM provides the slow linear motion and REVO does the fast demanding 5 axis movements.

The REVO system comes with a range of different probe heads for specific applications. Additionally, the interchangeable heads allow optical inspection and surface finish probes to be utilised.

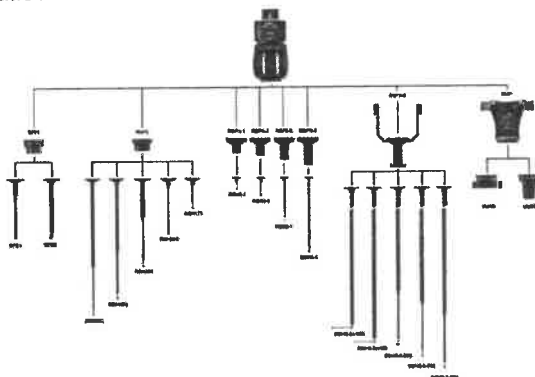


FIGURE 7. REVO interchangeable heads

In addition to 3D touch-trigger measurement, REVO is capable of tactile scanning with full 5-axis motion. The REVO Surface Probe (RSP3) system operates in a similar manner to the touch-trigger probes but rather than being triggered through an electrical kinematic connection, it utilises a laser beam incident along the bore of the stylus to the probe head and reflected back to a collector in the REVO head. The probe stays in continuous contact with the surface and as it moves and the deflection of the beam is measured. This makes it an excellent method of measuring freeform AM surfaces.

This system enables millions of measurement points to be collected on complex surfaces at ultra-high speeds when compared to traditional CMM giving incredibly detailed and accurate surface measurement. Accuracy is generally $< \pm 1 \mu\text{m}$ in addition to the CMM manufacturers quoted tolerances.

With the REVO system collecting millions of points on complex surfaces, visualising and the data enables operators to identify exactly where distortion is occurring so that parts and the AM process may be optimised to produce more accurate results.

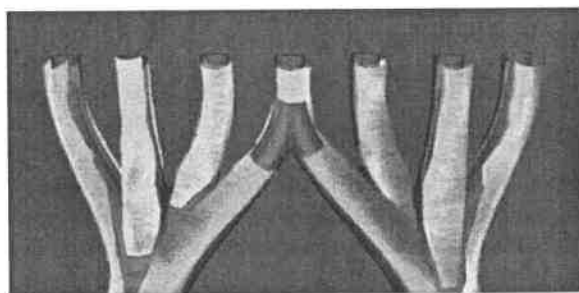


FIGURE 8. Visualisation of 10 million points

Taking advantage of the infinite positioning capability of REVO, the Renishaw Surface Finish probe (SFP) is another very important inspection tool. The surface measurement capability is from $6.3 \mu\text{m}$ to $0.05 \mu\text{m}$ ($250 \mu\text{in}$ to $2 \mu\text{in}$) R_a and within this range, achievable accuracy is $\pm 10\%$ allowing the probe to be used to characterise both unfinished and machined AM surfaces.

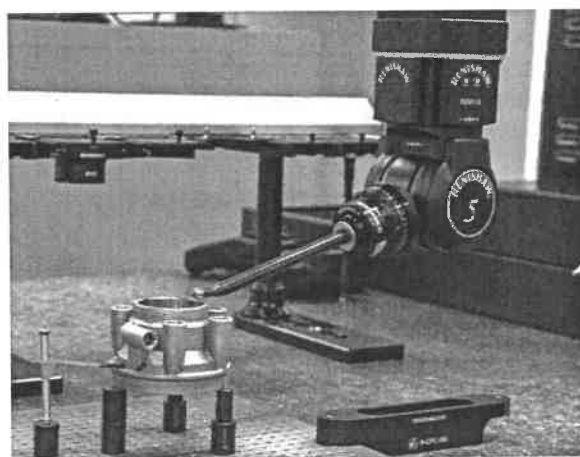


FIGURE 7. REVO 5-axis surface finish probe

In situations where tactile probing is not preferred, the REVO Vision Probe (RVP) may be

utilised. RVP is an optical inspection camera that is ideally suited to AM measurement and inspection. It can probe small holes and features (typically 0.5 – 1 mm diameter) that it would be difficult to access or measure accurately with a touch probe. RVP is also utilised in situation where contact probing could distort or damage the delicate parts making it ideal for inspecting delicate lattice features.

The results of camera inspection are not as accurate as tactile probing but the RVP has two lens options with 20 μm and 40 μm respective pixel resolutions and can achieve sub pixel accuracy which is generally well within the AM part requirements.



FIGURE 9. Renishaw vision probe

CONCLUSION

This paper discusses the solution approach that Renishaw use to guarantee quality and accuracy in AM production. Innovations in the QuantAM build preparation software such as bridge scanning and intermittent point scanning are the result of extensive experience in AM applications and brings key improvements to AM toolpath definitions. The RenAM500M is the first machine to exhibit a Renishaw engineered optical module and control system bringing an extremely high level of positional control and resulting in Renishaw's most accurate AM parts to date.

Most importantly this paper outlines how the AM system interacts with Renishaw's core groups of inspection technology. The Equator gauging system is shown to provide a fast reliable go/no go gate at each stage of manufacture. The Sprint on-machine probe and NC Perfect Part software are used to align AM parts for subtractive

finishing operations, ensuring that the part tolerances of which the AM process was not capable are met during finishing operations. Finally the REVO system with its adaptable heads for 5-axis tactile scanning, surface finish measurement and optical inspection have been shown to provide full CMM inspection capabilities.

All of these technologies combine to ensure that AM parts meet the same exacting standards as any other manufacturing process.



FIGURE 9. Fully inspected additive manifolds with subtractive finishing on key interfaces

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EVOLUTION OF SURFACE TEXTURE AND CRACKS DURING INJECTION MOLDING OF FIBER-REINFORCED, ADDITIVELY-MANUFACTURED, INJECTION MOLDING INSERTS

Thomas Hofstätter¹, Michael Mischkot¹, David B. Pedersen¹,
Guido Tosello¹, Hans N. Hansen¹

¹Department of Mechanical Engineering, Technical University of Denmark
Produktionstorvet 427A
2800 Kongens Lyngby
Denmark

Keywords: Additive Manufacturing Technology, Fiber-Reinforcement, Digital Light Processing, Carbon Fibers, Injection Molding, Surface

ABSTRACT

This paper investigates the lifetime and surface deterioration of additively-manufactured, injection-moulding inserts. The inserts were produced using digital light processing and were reinforced with oriented short carbon fibers. The inserts were used during injection molding of low-density polyethylene until their failure. The molded products were used to analyse the development of the surface roughness and wear. By enhancing the lifetime of injection-molding inserts, this work contributes to the establishment of additively manufactured inserts in pilot production.

INTRODUCTION

Prior experiments with digital light processing (DLP) or similar technologies and fiber-reinforced photopolymer have been performed showing the possibility of manufacturing parts using this process [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The possibilities of additive manufacturing (AM) for injection molding (IM) were already pointed out earlier in [12, 13, 14, 15]. However, the effect of fibers for the lifetime and surface deterioration of the IM inserts was not yet extensively investigated, although significant advantages at the cost, environmental and efficiency levels can evolve.

The fiber-reinforced polymer (FRP) showed a directional placement of the fibers within the manufactured layers allowing the reinforcement of the insert in two directions [9]. The lifetime of additively manufactured inserts made from photopolymer using DLP is located below those of inserts made from brass or steel as supported by [16, 17]

and, therefore, lifetime in terms of surface quality was the subject of this investigation.

This research contributes to the development of new technologies for injection-molding inserts reducing production costs as well as the environmental impact of prototyping and proof-of-concept manufacturing. It was pointed out by [18] that composite materials for IM inserts made from polymer and copper particles improved the heat conductivity of the inserts by increasing the lifetime of the inserts. This investigation was developed further using short carbon fibers.

METHODS

The IM inserts were produced using DLP from a photopolymer resin with 5 %wt short carbon fiber content equipped with an average diameter of 7.2 μm and an average length of 100 μm extending the research performed by [19] without fiber reinforcement. The layers were placed perpendicular to the expected pressure tensor from the polymer melt from the injection molding process resulting in a fiber placement in the manufacturing layers. The back and sides of the inserts were milled to reduce warpage of the inserts and increase the accuracy of the mold assembly.

The inserts were used during manufacturing with an IM machine injecting low-density polyethylene (LD-PE) at 210 bar maximum injection pressure during a 3 s filling time followed by a 10 s packing time and 10 s cooling phase for the insert in order for the insert to cool down to a temperature of 36 °C. The insert dimensions were 20 x 20 x 2.7 mm³. The total cycle time of the molding was 23 s.

The additively-manufactured insert was built into a multi-functional frame in the IM machine as shown in Figure 1. The LD-PE was injected from

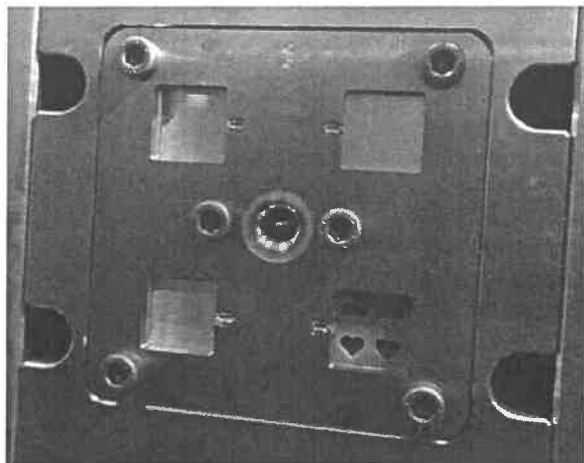


FIGURE 1. Single insert in the IM machine before the first shot.

the reverse side of the insert and through channels guided to the mold. The final part before ejection can be seen in Figure 2.

Tests of the surface structure in terms of roughness were performed using a focus variation 3D microscope system with a vertical resolution of 500 nm and a lateral resolution of 3 μm . The data of the scanned surface was thereafter aligned using global levelling for the inspected areas. The mean roughness was thereafter determined.

Moreover, a scanning electron microscope (SEM) JEOL JSM-5900 was used showing the deterioration of the surface during the molding process. A Dino-Lite Pro AM 4000 digital microscope was used to inspect the surface of the inserts and the parts after the molding process.

RESULTS

During this investigation, the observations in [9] concerning outstanding carbon-fibers at the border of the object were confirmed as the first manufactured parts showed residual carbon fiber material in the upper layer of the part. The outstanding fibers broke off after the first shot and stuck to the produced part. No residuals were found at the second shot and later. The outstanding fibers in the original IM insert are shown in Figure 3. It shall be noted that no fibers are standing perpendicular to the top surface layer.

Surface investigations of produced parts showed cracks of the insert in the μm regime after about 300 shots leading to a change in roughness of the surface of the manufactured part. Compared to other tests on photopolymer inserts without fiber-

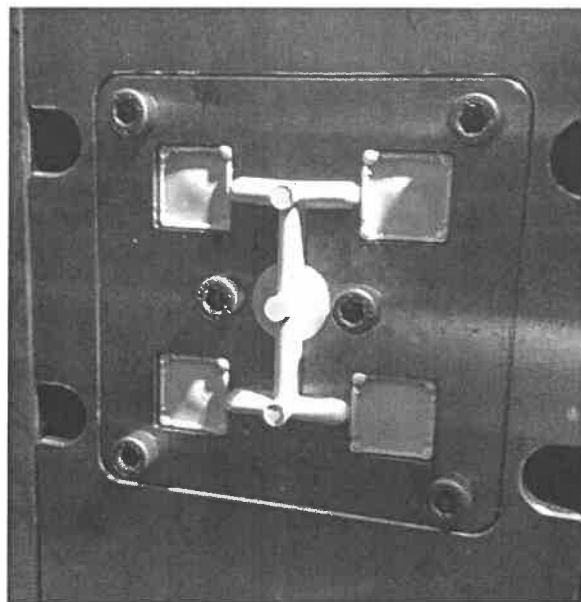


FIGURE 2. PE-LD parts arranged in the IM machine.

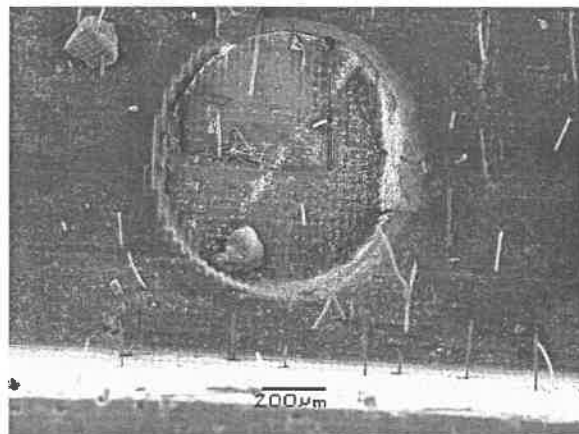


FIGURE 3. Fibers standing out of the produced layers in a SEM investigation confirming the findings in [9]. The image was taken before the first shot. The raster pattern on the surface results from the DLP process and the projector resolution.

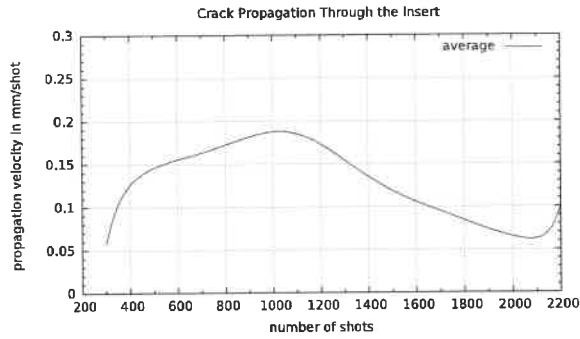


FIGURE 4. Crack propagation velocity over the number of shots (averaged).

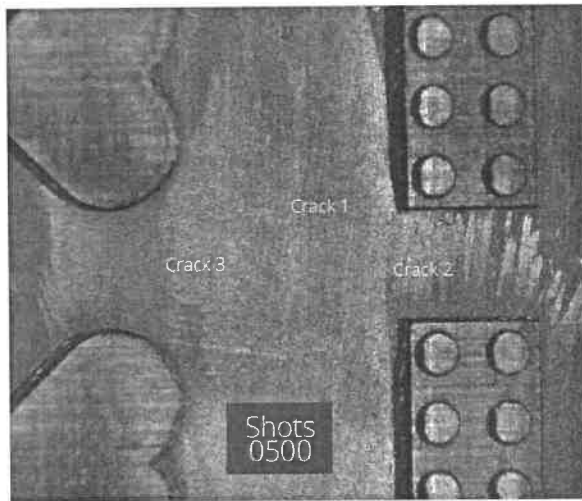


FIGURE 5. Cracks in the insert after shot 500.

reinforcement [19], the enlargement and lengthening of the cracks were significantly reduced allowing a continued production up to several hundred parts.

The crack propagation had an average velocity of 0.145(34) mm/shot after the first sign of the crack until the failure of the part. Figure 4 shows the averaged crack propagation velocity over time showing an increase of the velocity up to 0.19 mm/shot followed by a decrease until failure of the insert. The crack propagation is visualized in Figure 5 to Figure 8 showing the first cracks at shot 500. Crack 2 is blocked by crack 1 after shot 1300 and therefore does not propagate any further. Note also the degradation of the edges as can especially be seen in the round parts on the left side of the figures. Crack 3 also propagates on another level on the lower part after shot 1300.

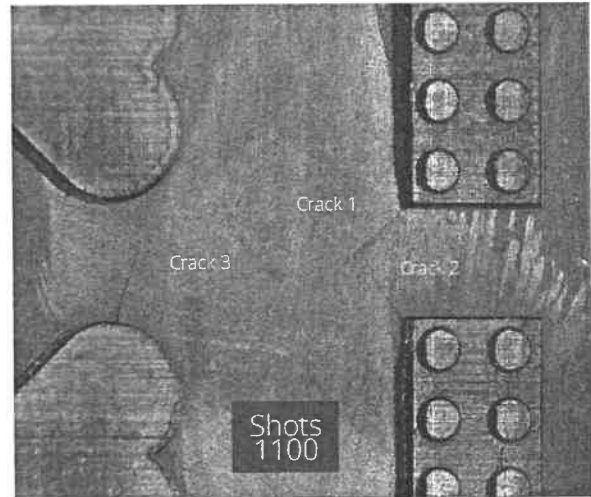


FIGURE 6. Cracks in the insert after shot 1100.

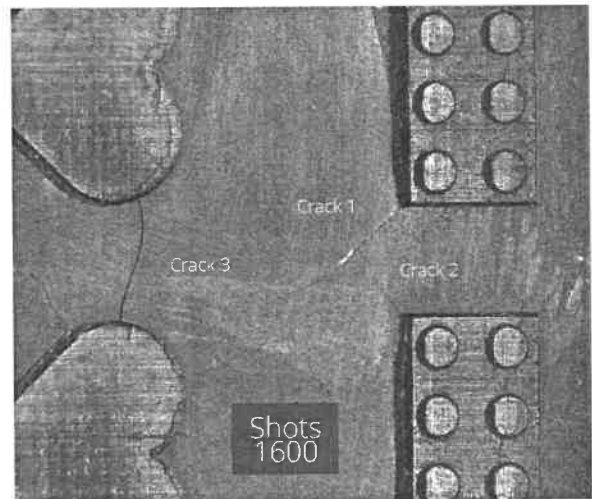


FIGURE 7. Cracks in the insert after shot 1600.

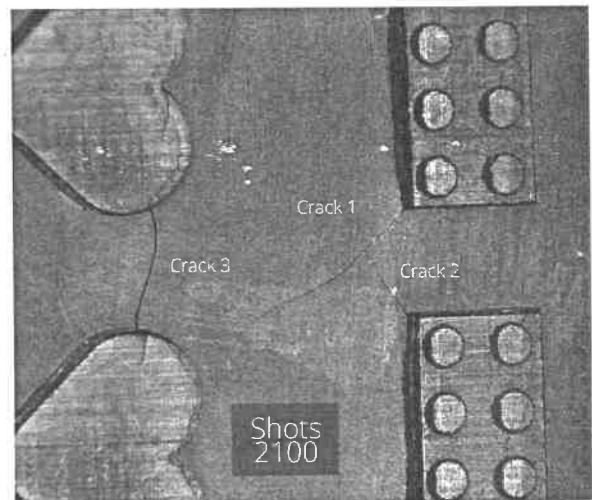


FIGURE 8. Cracks in the insert after shot 2100.

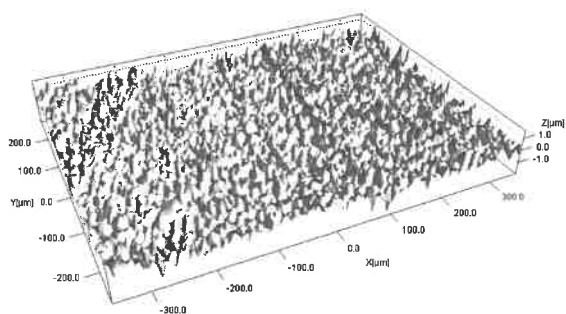


FIGURE 9. Graphical representation of the surface roughness after 10 shots showing the profile under a focal variation 3D-microscope in the middle of the insert.

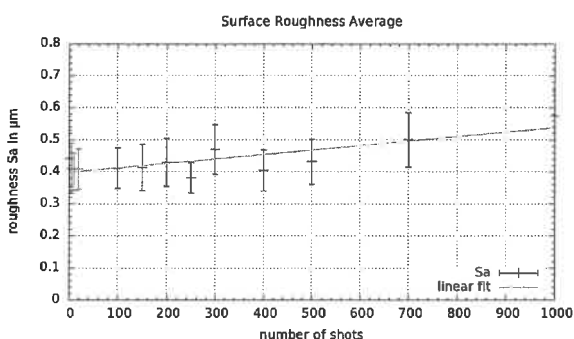


FIGURE 10. Averaged roughness propagation during the first 1000 shots neglecting bigger cracks in the surface.

A graphical representation of the surface of an insert in Figure 9 shows a central surface area with respect to height variations and roughness of the surface. The figure allows conclusions about scratches that were produced during the milling of the insert before the first shot.

Surface roughness despite bigger cracks evolves linearly according to the formula:

$$Sa(\text{shot}) = a + b \cdot \text{shot}$$

$$a = 0.398128 \pm 0.01219$$

$$b = 0.000138742 \pm 3.014 \times 10^{-5}$$

which allows the conclusion that the changes in the general surface roughness can be neglected. The average surface roughness was calculated over 7 inserts with respect to the first 1000 shots (see Figure 10).

The analysis of the surface degradation showed the impact of the fibers within the polymer by re-

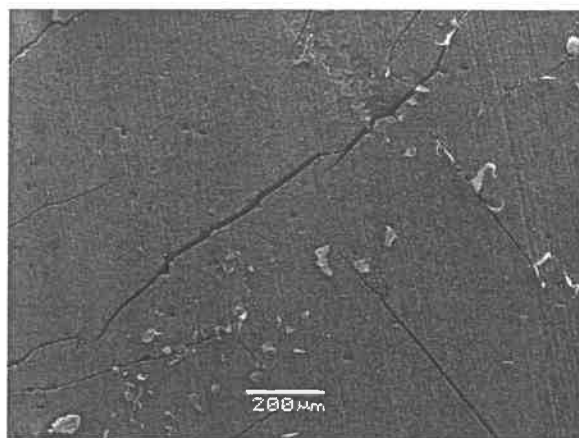


FIGURE 11. Surface cracks in the insert after 2658 shots under an SEM, the debris result from PE-LD stuck in the cracks

ducing the speed of crack propagation within the insert allowing for the running of shots producing parts with a smooth surface appearance although cracks were already present in the insert. The lifetime was investigated by the consideration of cracks on the surface or throughout the entire insert. Cracks producing a flash that was clearly visible without magnification were considered a failure of the insert. It could be shown that the crack propagation was reduced by inserting the fibers in a layer standing orthogonally to the crack orientation. In this way, the fibers contributed better mechanical properties in terms of strength and durability.

Cracks of the insert were reduced to surface cracks as shown in Figure 11 after 2658 shots with low propagation speed and gap size in the range of 1 to 5 μm . Most cracks originated from the edges in the surface of the insert as shown in Figure 12. Those were degrading in such a way that the edges became round as can be seen in Figure 13.

Figure 12 includes parts of the surface protected against thermal and mechanical strain. No cracks evolved in the protected part of the surface and no cracks originated at its border.

The cracks were reproduced in the molded part in the form of flashes for low gap sizes. At larger shot numbers, PE-LD got stuck in the gap as shown in Figure 14 as a detail of Figure 11 and therefore caused severe damage to the produced part. The insert was then characterized as destroyed.

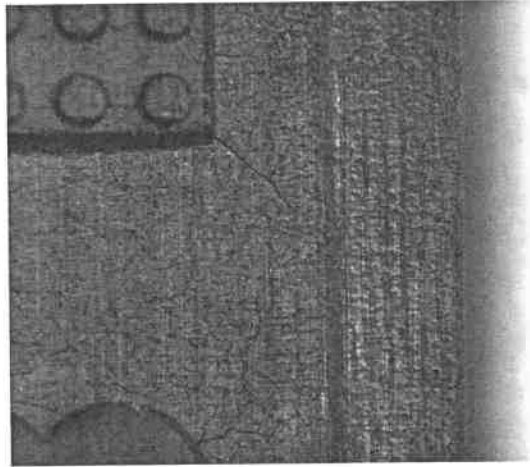


FIGURE 12. Insert surface after 2658 shots showing crack origin at edges as well as parts of the protected surface without cracks.

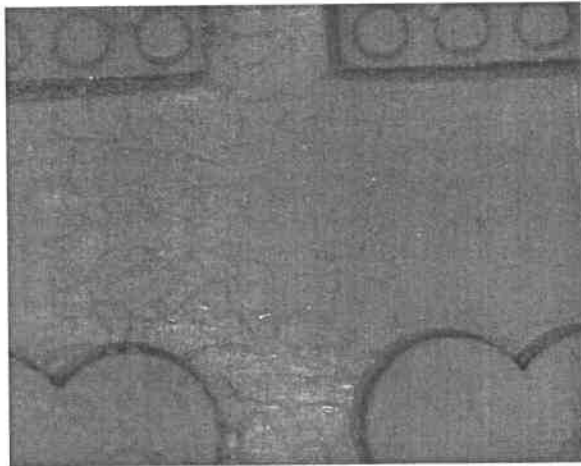


FIGURE 13. Part surface and rounded edges after 2658 shots.

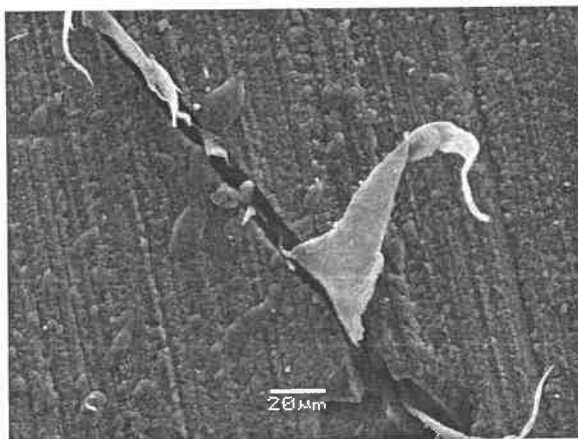


FIGURE 14. Detail of surface degradation with PE-LD material stuck in the crack.

An average number of shots of 2580 was gained using the fiber-reinforced inserts. Compared to the non-fiber-reinforced inserts, the experiments resulted in an increase of the number of shots by 500 %. Crack propagation was reduced to 1.25 % of the velocity in the plain insert.

CONCLUSION

It can be concluded that the lifetime of fiber-reinforced IM inserts could be extended compared to plain IM inserts. The surface wear in terms of mean surface roughness was negligible when inspecting the surface without crack-like features.

Minor racks on the surface appeared early from 300 shots but did not propagate to major cracks, and therefore did not result in fatal failure of the entire insert.

Propagation of major cracks through the entire insert were found to spread slower compared to plain inserts. Thus, it can be concluded that the lifetime of the insert was increased by generating a composite using short carbon fibers.

Additively-manufactured, fiber-reinforced inserts can be considered suitable for pilot production with low part numbers, and therefore are an alternative to more expensive inserts made from brass or steel.

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DISTRIBUTION AND ORIENTATION OF CARBON FIBERS IN POLYLACTIC ACID PARTS PRODUCED BY FUSED DEPOSITION MODELING

Thomas Hofstätter¹, Ingomar W Gutmann^{2,3}, Thomas Koch⁴,
David B. Pedersen¹, Guido Tosello¹, Gertraud Heinz², Hans N. Hansen¹

¹Department of Mechanical Engineering, Technical University of Denmark

²Institute for Radiology and Intervention, University Hospital St. Pölten,
Karl Landsteiner University of Health Sciences

³Faculty of Physics, University of Vienna

⁴Institute of Materials Science and Technology, Vienna University of Technology

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ABSTRACT

The aim of this paper is the understanding of the fiber orientation by investigations in respect to the inner configuration of a polylactic acid matrix reinforced with short carbon fibers after a fused deposition modeling extrusion process. The final parts were analyzed by X-ray, tomography, and magnetic resonance imaging allowing a resolved orientation of the fibers and distribution within the part. The research contributes to the understanding of the fiber orientation and fiber reinforcement of fused deposition modeling parts in additive manufacturing.

INTRODUCTION

A literature review of research on fiber-reinforced polymers in additive manufacturing using mainly glass and carbon fibers showed that prior work in the field of FRPs in FDM has already been performed by [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11] investigating the direction of fiber-reinforced Fused Deposition Modeling (FDM) using carbon and glass fibers in an Acrylonitrile Butadiene Styrene (ABS) or polylactic acid (PLA) matrix and discussing the strengthening of the material as well as the fiber orientation. An overview of the increase of tensile strength and Young's modulus achieved by the above-mentioned sources using FRP in FDM is shown in Figure 1 and Figure 2. The preliminary data of Figure 1 and Figure 2 may be suggestive of trends, but due to its tentative nature we voluntarily abstained from implying any quantitative relation by fitting a regression model.

Investigations of the final part were performed using a JSM-5910 Scanning Electron Microscope

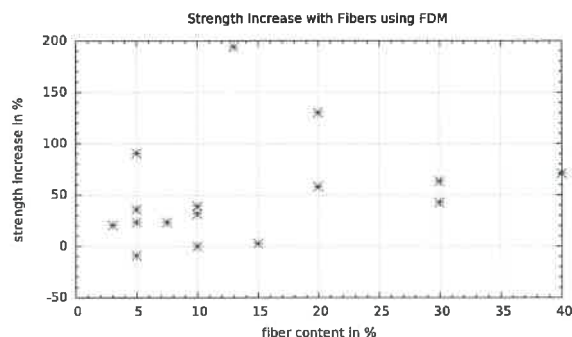


FIGURE 1. Increase of tensile strength according to literature research with different amounts of fibers.

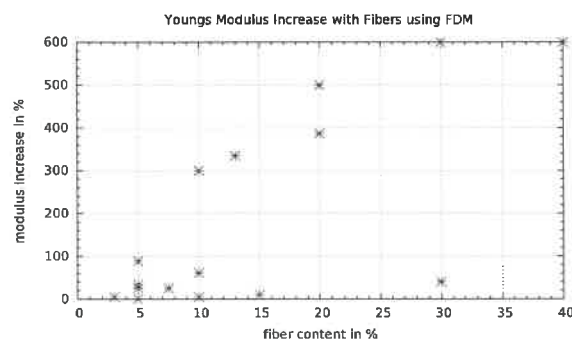


FIGURE 2. Increase of Young's modulus according to literature research with different amounts of fibers.

(SEM). Possibilities for the transmissive investigation of PLA are supported by [12] stating a continuous transmission of PLA of over 90 % at wavelengths of 250 nm and higher.

To investigate the spatial alignment, orientation and distribution density of the fibers within the printed part as well as the conformity of the printed results with the intended shape both on mesoscopic and macroscopic level, Radiological modalities like Computed 2-dimensional X-ray Radiography on photostimulated luminescence image storage plates (CR), Computed X-ray Tomography (CT) with human-grade multi-detector 128-line CT and research-grade micro-CT Scanners was performed. Finally, the material properties were explored with quantitative Magnetic Resonance Imaging (MRI) methods at 3 T.

METHODS

The parts were produced using PLA filament with 15 %_{wt} virgin short carbon-fiber content with average diameters of 7.2 μm and an average length of 100 μm . During the manufacturing process, the fiber-reinforced filament was heated over the material's glass-transition temperature and fed through a nozzle with a diameter of 400 μm . This resulted in an orientation of the carbon fibers along the path of the filament. This property could be used when aiming to reinforce the product in a certain main direction.

An orthogonal cut through the layers of the FDM print of the objects was performed, followed by a polishing finish in order to visualize features of 1 μm voxel size before the SEM investigation. Due to the layer-wise orthogonal alignment of the infill, the cut showed one layer along the line produced by the FDM nozzle and one cut orthogonal to the line allowing an elaboration on the orientation in three dimensions as well as the interface between the different extrusion directions.

Moreover, SEM investigations of the fracture surface were performed after a pull-test was performed until the failure of the part. The dog bones used for this investigation were produced by the above-mentioned FDM printer under layer-wise alternation of the printing direction in order to avoid globally anisotropic material properties in the final dog bone.

The printing paths are graphically represented in Figure 3 and Figure 4. The outer paths were tracked around the object to provide a higher sur-

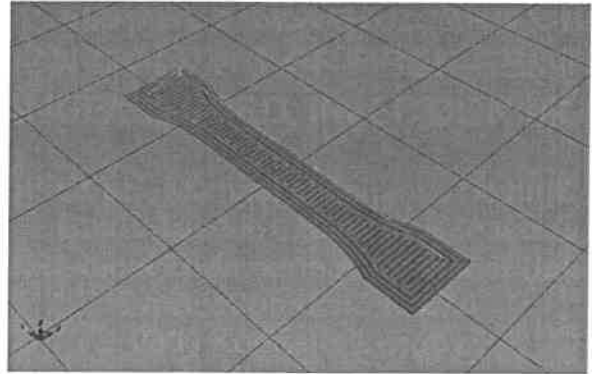


FIGURE 3. First layer geometry of the printed dog bone.

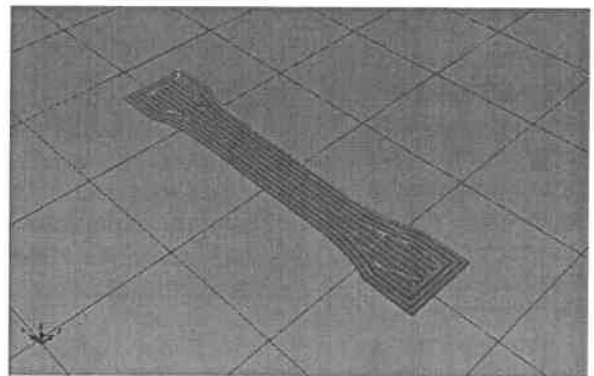


FIGURE 4. Second layer geometry of the printed dog bone.

face accuracy and a cohesion of the entire dog bone. By investigation of a single surface, cuts in two directions through the extruded filament as well as an investigation of the interface between the filament lines are possible.

This production method can be justified with the above-mentioned investigation aims of a detection of fiber orientation. Investigations aiming to find the increase of tensile strength or Young's modulus have chosen a fiber orientation entirely in longitudinal orientation.

This research contributes to the understanding of FDM processing with FRPs by observing the fiber orientation after the manufacturing and within the final part. The orientation of the fibers allows a directional reinforcement of the final part that may be manipulated on a mesoscopic level.

This material may offer susceptibility matching properties of greatest interest for Nuclear Magnetic Resonance (NMR) / nuclear MRI applications in technology as well as in medicine. In

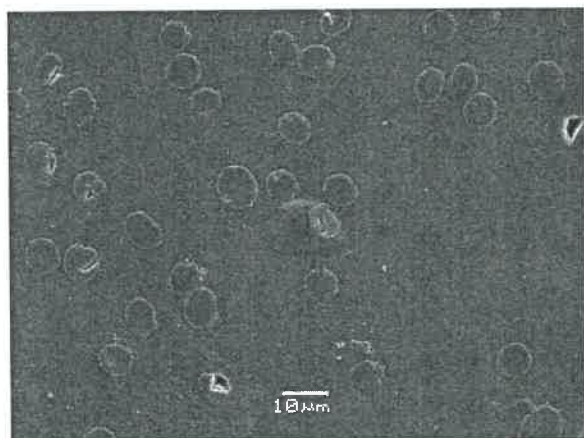


FIGURE 5. *Fiber orientation and interface to the PLA in a polished cut.*

their pioneering work, Lee et al. [15] showed the benefits of using Pyrolytic Graphite Foam as a passive magnetic susceptibility matching material. This material seems to have similar desirable properties and at the same time offers far greater mechanical strength whilst retaining the property of being able to be 3d-manufactured into desired shapes with readily available 3d-printers.

One possible further application to be pointed out is the individualised 3d-manufacturing of potentially medical implants. Conventional implants manufactured from non-ferromagnetic metals still retain a certain degree of resultant image artefacts in MRI and hence may hinder forthcoming examinations difficult to impossible.

Notwithstanding the tentative nature of the experience with the material and the clear implication of the strongest need for more research, the material may provide an easy to manufacture, lightweight and economically attractive solution.

RESULTS

Scanning Electron Microscopy

The polished cut through an extrusion line shows the interface between the carbon fibers and the PLA matrix in Figure 5. The interface neither exhibits gaps between the fiber and the matrix nor cracks in the matrix. The detailed view in Figure 6, nevertheless shows deformed and destroyed fibers. The bottom-right corner of the image shows a part of the matrix where the viscosity of the PLA-melt exceeded the possibilities of filling the sharp concave corners.

Significantly stronger influence can be stated for holes resulting from the manufacturing process in

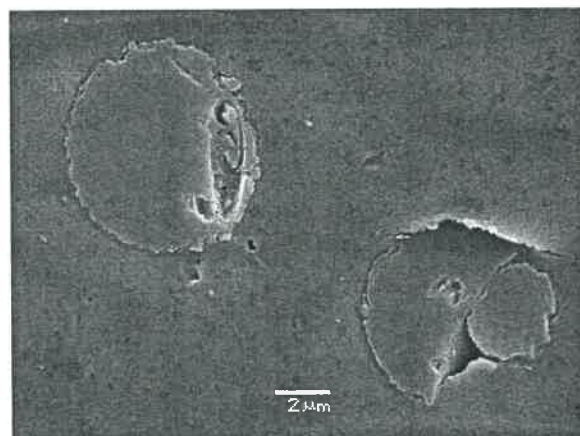


FIGURE 6. *Detail view of the interface between the fibers and the PLA matrix in a polished cut.*

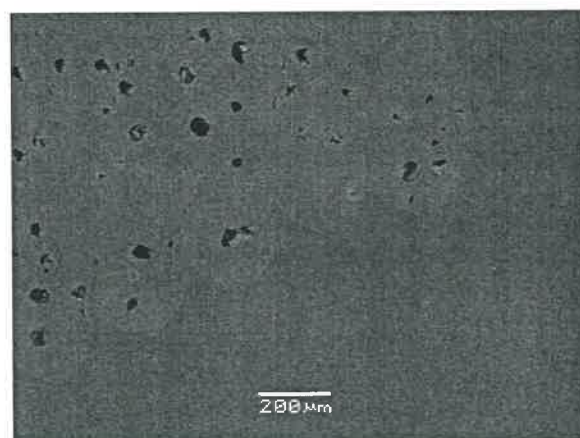


FIGURE 7. *Holes in the PLA matrix in a polished cut; variations in amount and size of holes at the different layers are visible.*

the FDM nozzle. The holes shown in Figure 7 result from the thermal setting of the nozzle.

The holes show a characteristic oval shape when cut longitudinally to the fiber orientation and a round shape when cut orthogonally to the fiber orientation allowing the interpretation of an ellipsoid shape with the major axis in the extrusion orientation. The same observation can be made in Figure 10.

The characteristic interface between the produced extrusion vanishes due to the remelting of the matrix polymer during the extrusion and deposition process. Intersection of differently-oriented fibers between the layers is visible in the fracture surfaces of Figure 8 which, together with Figure 9 and Figure 10, confirms again the orientation and size of the holes in the matrix material. Therefore,

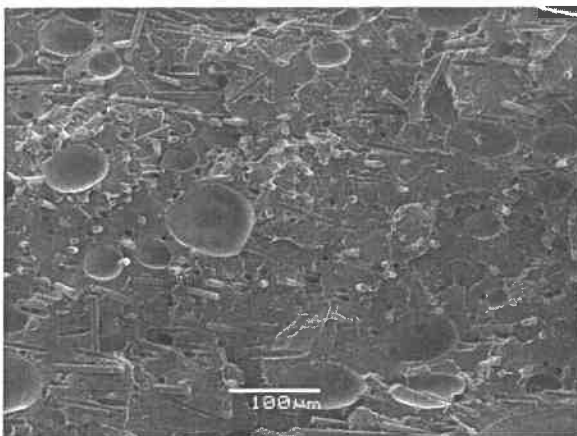


FIGURE 8. Fiber orientation according to the print direction on a fracture surface after a tensile test; orientation of the fibers in the direction of the extrusion.

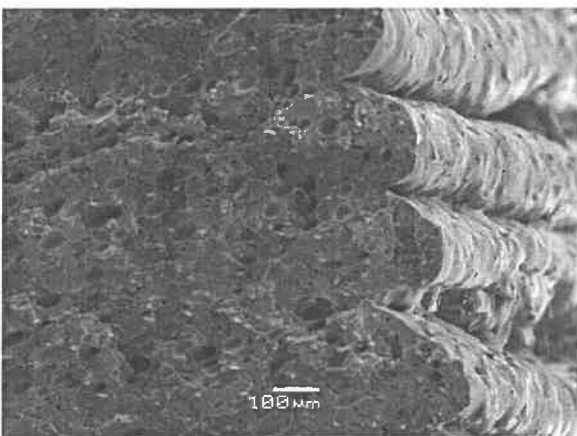


FIGURE 9. Holes in the PLA matrix on a fracture surface after a tensile test; variations in amount and size of holes at the different layers are visible.

the tensile strength is reduced by the disturbed matrix material.

Figure 8, Figure 9, and Figure 10 show the characteristic fiber orientation longitudinally to the extrusion path. Confirming the common theory of the effect of fiber orientation on tensile strength in FRP, the influence of the orientation on the fracture surfaces is shown by the high number of orthogonally oriented fibers missing in the fracture surface, whereas only 40 % of the fibers in a longitudinal orientation towards the tensile strength were pulled out of the matrix at the fracture surface.

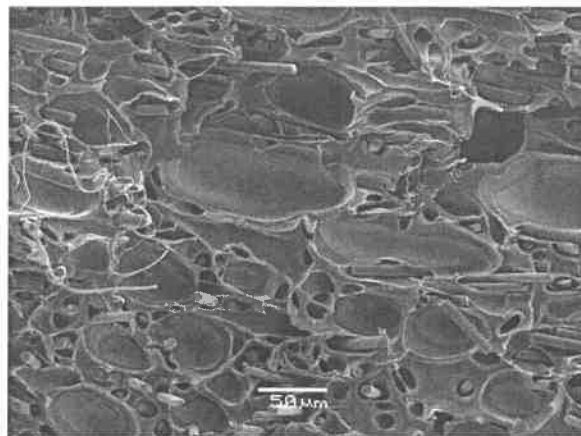


FIGURE 10. Detail of holes in the PLA matrix on a fracture surface after a tensile test; variations in orientation and size of holes at the different layers.

Radiological Imaging

In spite of all efforts and using a state of the art high end human multi-detector CT, the resolution limit for resolving fibers or even distribution densities remained too high to draw any conclusions that concur with the high professional level we desire. At the present moment, no apparent potential for using human grade multi-detector CT in determining the mesoscopic structure of materials is in our grasp. However, this may change with the rise of multi-energy and multi-beam technologies.

Cone Beam CT may provide a solution, as some manufacturers claim to provide devices with resolutions down to the order of about 10 μm on human (i.e. easily available) scanners.

Research grade micro-CT has the potential to provide deeper insight into the structure as shown in Figure 11. Clearly visible are fiber bundles, individual fibers and air inclusions in an extruded filament.

CR is proved to be most effective for this application, mostly due to its sufficient resolution, simple setup and uncomplicated availability.

Notwithstanding being at the edge of resolvability and certainly with some degree of spatial aliasing, it was possible, after optimisations using a carefully prepared honeycomb shaped geometry for the print with illumination lateral relative to the main axis of the honeycomb rhombic geometry, to work out details of the fibre bundle distribution.

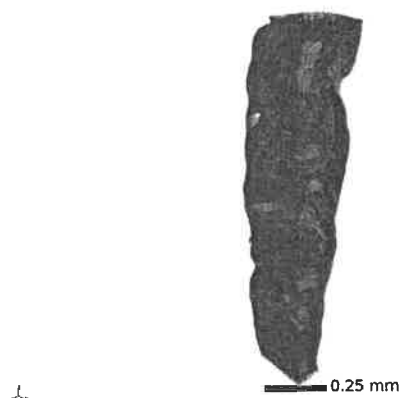


FIGURE 11. Freely extruded filament under CT investigation.

CONCLUSIONS

A conclusion can be drawn in terms of fiber orientation during the final part in strong relation to the printing orientation in the FDM process. Due to the two cycles of extrusion of the material (1) when generating the filament from granule; and (2) during the additive-manufacturing (AM) process, fibers were oriented longitudinally to the printing path.

Elipsoidal holes with the major axis in the nozzle orientation occurred in the PLA matrix with average sizes of 50 to 100 μm possibly resulting in a reduction of tensile strength. Compared to FRP in digital light processing (DLP), the size of the holes was significantly increased [16]. The distribution of fibers was therefore also influenced whereas the fibers were generally oriented in the middle of the extrusion line.

The interface between the layers was indistinct due to the remelting of material during the extrusion of the next layer allowing for a continuous matrix material. This also resulted in an interconnected orientation of longitudinally-oriented and orthogonally-oriented fibers.

The interface between the fibers and the PLA matrix was destroyed during the tensile-test. This was fatal at the layers with orthogonal fiber orientation towards the tensile strength. 40 % of all fibers in a longitudinal orientation towards the tensile strength were ripped out of the matrix at the fracture surface.

As a further line of investigation, is to proceed in investigating radiography of thin cut slices in order to minimize projective geometry and partial volume artefacts.

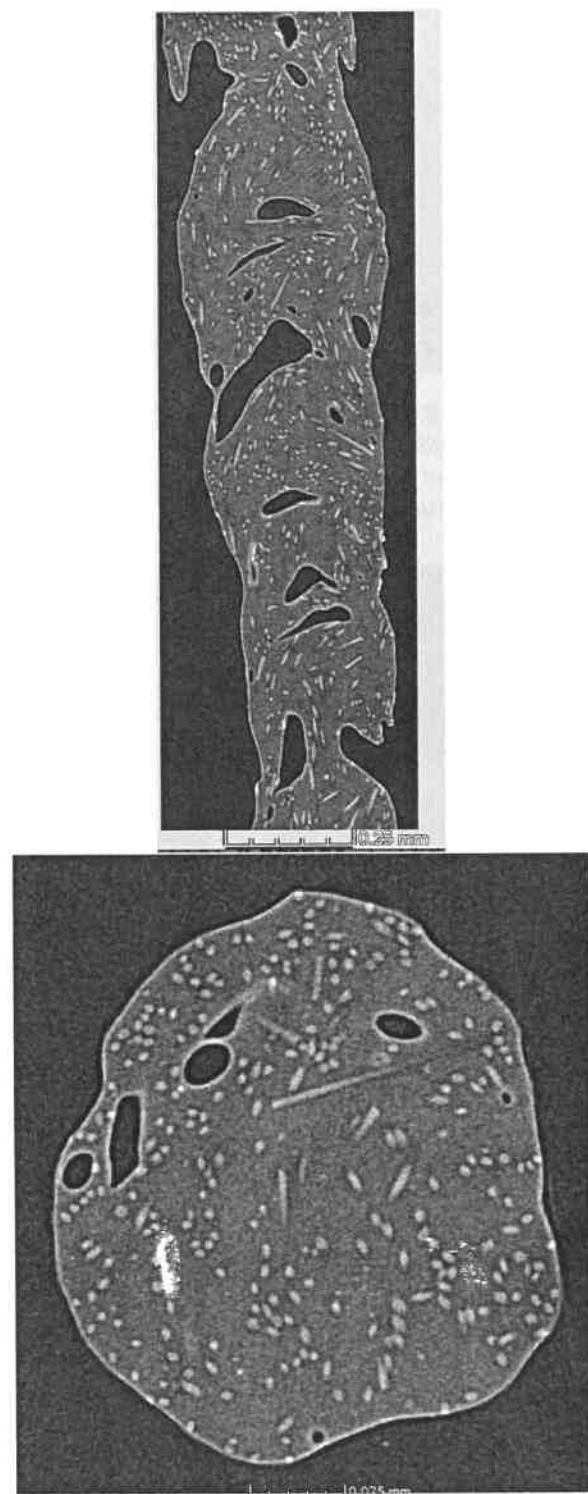


FIGURE 12. Transversal and medial lateral cut under CT investigation.

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SURFACE FINISH METROLOGY OF ADDITIVE-MANUFACTURED COMPONENTS

Zachary C. Reese¹, John S. Taylor^{1,2}, and Chris J. Evans¹

**¹ Center for Precision Metrology
University of North Carolina at Charlotte
Charlotte, NC 28223**

**² Lawrence Livermore National Laboratory
Livermore, CA 94550**

INTRODUCTION

Metal Additive Manufacturing (AM) is a rapidly expanding technology in both the research and industrial sectors which utilizes a layer by layer build process to fabricate parts directly from 3-D CAD models. AM encompasses a number of distinct process categories that take advantage of layer based fabrication to create prototypes or finished parts with remarkably complex geometries. The ability to produce these intricate parts sets AM apart from traditional manufacturing methods such as milling, turning, casting, etc. That being said, these parts are limited by their poor "as printed" surface quality. Finishing operations (e.g. bead blasting, milling, laser ablation) can be utilized to improve the quality of their surfaces. However, it is common for some of these surfaces to be left in their "as printed" state. This could be due to an inability to reach these surfaces with post processing methods, or the surfaces were deemed non-critical and left unaltered to save time and cost. In any case, obtaining a better understanding of AM surfaces is critical step in pushing this technology forward [1].

Additive components, especially those created through powder bed fusion processes such as Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS), exhibit an abundance of surface textures of varying forms and patterns. These intricate topographies are generally described and categorized using nothing more than their R_a values. While this method is serviceable, current instruments have the potential to provide other useful, and potentially more significant information about metal AM surface morphology. With this information it will be possible to create a richer language to describe "as printed" AM surfaces and eventually relate the process parameters to the morphology of the final part. In powder bed fusion AM processes, there are a vast number of

input parameters such as laser power, laser scan speed, scanning strategy, bed pre-heat, layer height, etc. With this large array of variables, it is unlikely that direct correlation between inputs and the printed part will be trivial or reached without this crucial intermediate step. This research expands upon the idea that a strong link between surface morphology and process parameters is a necessary step in the understanding and further implementation of metal additive manufacturing. This connection is being made through rigorous cataloging and characterization of surface features to find a link to the physical build process.

DROPOUT INVESTIGATION

It was decided that areal measurement techniques would be required to fully assess the features present on the surfaces of these parts. This decision narrowed the amount of available options to three optical profiling machines. Due to the steep slopes and high roughness seen in these "as printed" surfaces, data dropout is prevalent when measuring parts using optical methods. The focus of this stage of research was to find what instrumentation and setup can be used to cut down on the number of data dropouts, as well as accurately identify surface form and features. For this comparison, the same area map was captured on a Zygo ZegagePlus Scanning White Light Interferometer (SWLI), a LEXT Olympus 4000 Confocal Microscope (both located on campus at UNCC), and a Zygo Nexview SWLI (located at Corning Optical Communications in Hickory, NC). The percentage of dropped pixels was measured in each. Figure 1 shows one such area map compared across the three instruments along with the percentage of data dropout present in each. For the part measured, all maps followed this trend. The Zygo Nexview experienced the least amount of data drop, followed by the Zygo ZegagePlus, and last the

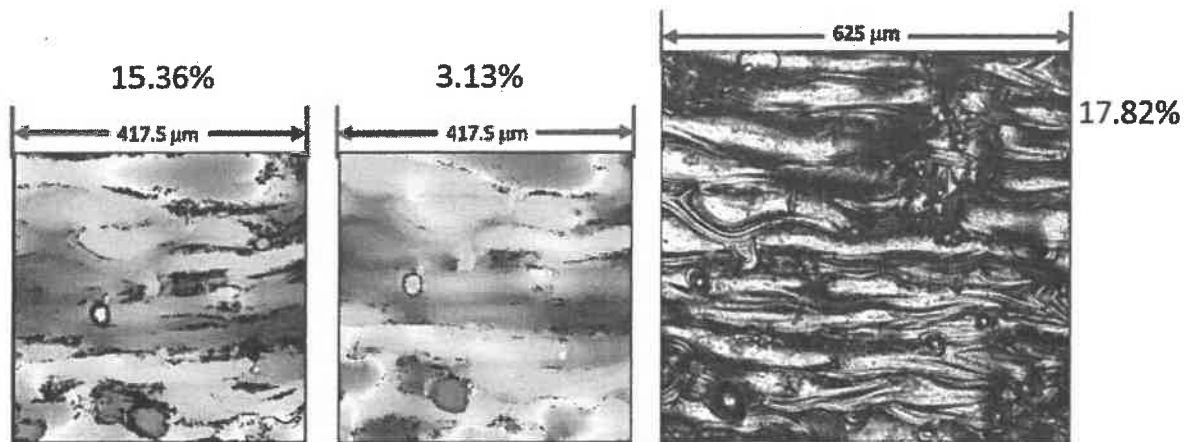


FIGURE 1. Data drop comparison among Zygo ZegagePlus, Zygo Nexview, and LEXT Olympus 4000 (left to right).

LEXT Olympus 4000. Though the Nexview experienced significantly less dropped data points than the other two instruments, it was decided to use the ZegagePlus in all measurements moving forward for accessibility reasons. It should also be noted that data dropout seen in the ZegagePlus was significantly smaller in parts that were measured later in this research (as low as 1.01%).

FEATURE EXPLORATION

Once the form of these surfaces could be measured with minimal dropouts the focus shifted to surface parameters and features. For this portion of the investigation, attention was turned to the top surfaces of the part shown in figure 2.

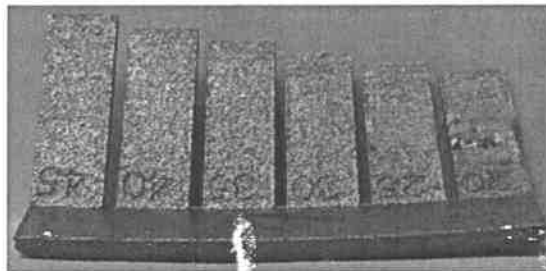


FIGURE 2. Top surface of tabs on NCSU-1

This piece was provided by Dr. Ola Harrysson's lab at North Carolina State University (NCSU) and provided a wider variety of build shapes than had been examined prior. The part (hereafter referred to as NCSU-1) was made of a titanium alloy and printed on an EOS printer using DMLS. NCSU-1 is made up of six tabs printed from 20° to 45° in 5° increments. All tabs were printed without any supporting structures which would allow for future study to be

conducted on the downward surfaces as well. Although none of the input parameters were known about NCSU-1, it had the potential to provide a lot of information not previously seen in other pieces measured in this research.

Scan/Step Frequency and Roughness Parameters

Upon first inspection of the top surfaces of the NCSU-1 tabs, many features made themselves readily apparent. After looking at representative area maps from each tab, a clear, qualitative difference in the scan/step frequency of each was noticed. Multiple areal map stitches were then taken perpendicular to the scan direction to quantify these preliminary results. Five stitched area maps were taken along the length of each tab (orientation and example stitched map shown in Figure 3). Each of these maps were subjected to PSD analysis in the "y" direction in an effort to isolate this ringing frequency. The results were averaged for each tab and plotted against tab angle (Figure 4).

The same stitched maps were utilized in the calculation of areal and profile roughness parameters. For each map, areal roughness (S_a) is calculated over the entirety of the map using MX, Zygo's most recent software package. Profile roughness (R_a) values were calculated using several profiles taken in the "y" direction (see Figure 3) over each area map. Profile roughness was averaged for each tab and plotted alongside the S_a values for each tab as shown in Figure 5.

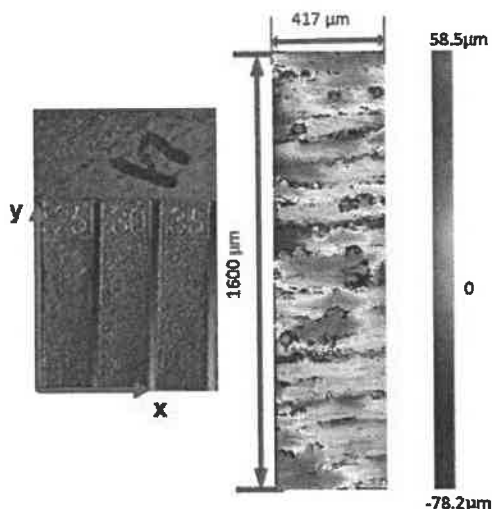


FIGURE 3. Scan orientation and 5x1 stitch of 30° tab. 20x objective

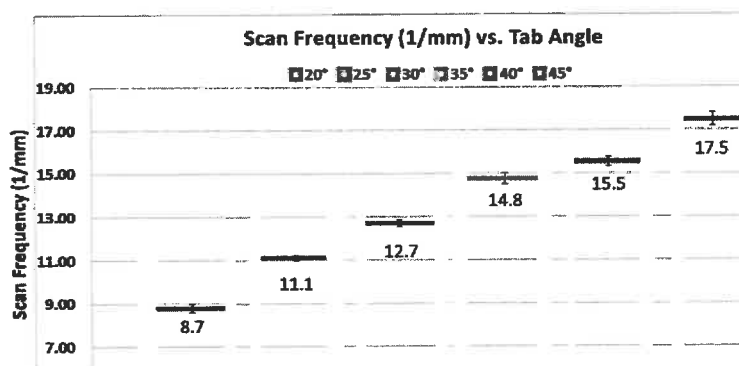


FIGURE 4. Scan frequency vs. tab angle (Angle increasing from left to right. Error bars depict 1 standard deviation)

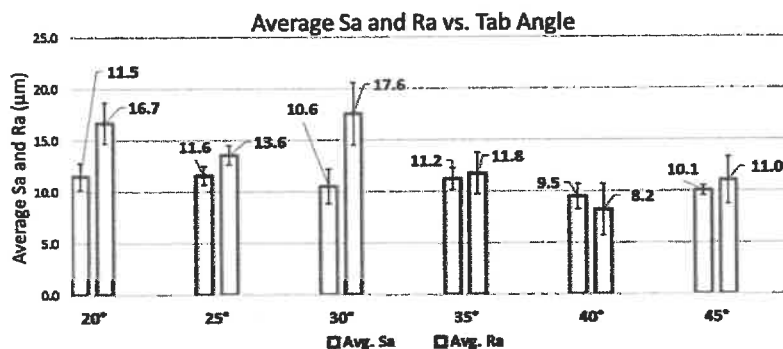


FIGURE 5. S_a and R_a vs. tab angle (left: S_a , right: R_a . Error bars depict 1 standard deviation)

From Figure 4, it can be seen that the scan/step frequency increases monotonically with the angle of the build. This leads one to believe that it is, in fact, the step height of the build being picked up by the PSD as the layers need a larger offset to make a shallower build angle. This data shows that each tab has a surface that is, to some extent, different from the others on the part. This difference, however, is not reflected in the roughness data shown in Figure 5. No discernable pattern can be picked up across scan lines and mostly overlap with one another at one standard deviation. These results add merit to the belief that roughness parameters do not communicate all that is needed to be known about AM surface morphology.

Chevron patterns

While completing the work on scan/step frequency, a distinct chevron pattern could be seen across the tops of scan lines (Figure 6). This pattern appears to be quite similar those seen after laser welding operations, and mirrors the shape seen at the rear of the melt pool during laser based AM. These observations lead the authors to believe that this pattern may be viewed as a process signature. Moving forward, quantification of this pattern could aid in the connection between the surface morphology of AM parts and many process parameters such as scan direction, scan speed, laser power, whether or not the laser was pulsed, and depth of penetration.



FIGURE 6. Chevron pattern. 50x objective, live image.

Hills and Pits

As with most unfinished AM surfaces, hills created through either spatter effects or partially melted particles exist throughout the top surfaces of these tabs. Spatter effects from the melt pool have been well documented in AM research. It has been noted that excessive laser input and heat generation in a part can increase these spatter effects [3], but these results have not been quantified. Separation and quantification of these features proves to be a challenge, but could lead to insights about the laser based AM process. Preliminary attempts have been made in this research to separate these features using water shedding (Figure 7), but quantification of these separated features has yet to return results.

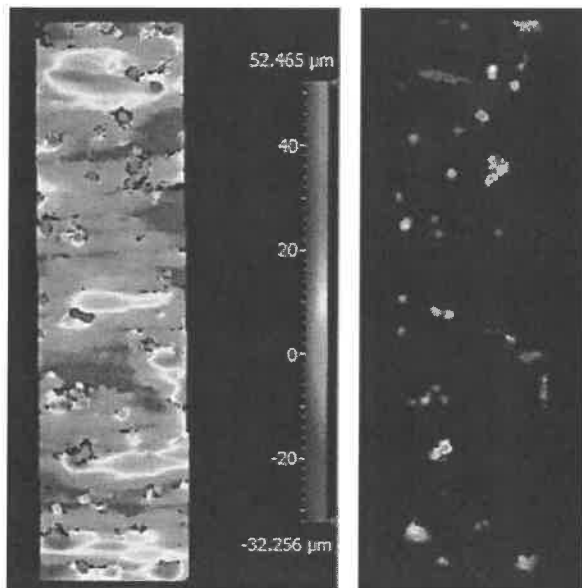


FIGURE 7. Preliminary segmentation of hills using water shedding

Perhaps the smallest persistent feature exhibited in this part are small 'pock mark' like pits in the surface. These pits are quite small (on average only 1-2 μm deep and 3-4 μm in diameter) and tend to be dwarfed by other features and scan lines. They seem to be present anywhere that this part exhibits an overhung feature, which on its own is not telling of anything that could not be ascertained on a macro scale. However, it has been noted that pits increase in population in the over-melted regions of the 20° and 25° (Figure 8). Though all pit analysis is qualitative at this time, further exploration of these features may be worthwhile as this research progresses.

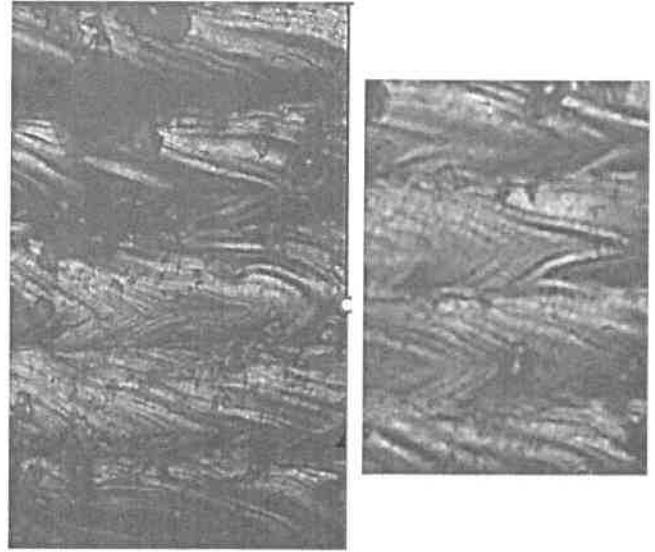


FIGURE 8. Pits present in the overmelted region of the 20° tab (left) compared to normally melted region (right).

CONCLUSIONS

The surfaces of additive manufactured components are rich with features that have the potential to be much more informative than the currently accepted parameters. Understanding these features is a crucial in making a connection between the surface morphology of a part and the process parameters used in its creation.

FUTURE WORK

Moving forward, a plan is in place to intensively study the chevron patterns and how they are affected by altering process parameters.

Improved water shedding and motif analysis techniques will be utilized in an effort to separate and quantify hills and pits.

ACKNOWLEDGEMENTS

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AUSPICES

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Surface finish inspection by X-ray Computed Tomography in FDM parts

Leopoldo Ruiz-Huerta^{1*}, Homero Castro-Espinosa², Alberto Caballero-Ruiz¹

¹Laboratorio Nacional de Manufactura Aditiva, Digitalización 3D y Tomografía Computarizada (MADiT)

Centro de Ciencias Aplicadas y Desarrollo Tecnológico (CCADET)

Universidad Nacional Autónoma de México (UNAM)

Circuito Exterior S/N, Ciudad Universitaria AP 70-186, C.P.

04510, México D. F. México

²Programa de Maestría y Doctorado en Ingeniería, Universidad Nacional Autónoma de México, Ciudad de México, 04510, México

leoruiz@unam.mx

ABSTRACT

Additive manufacturing (AM) is defined by ASTM as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining [1].

Among additive manufacturing (AM) technologies, material extrusion systems represent one of the largest installed base of AM machines [2]. Fused deposition modeling (FDM) technology is a melt extrusion process where a filament is selectively extruded through a nozzle tip or orifice. In this process there must be, at least, two materials extruded: the building model material (the material of the final component) and the support material, necessary when parts of the device built is in cantilever [3] [4].

Because the filament is deposited layer by layer, the surface of the parts produced by FDM has ridges. This effect is present on the inclined surface of the parts and is known as the *stair stepping effect*. Such an effect is shown in Figure 1 [5].

In this work, a study of the impact on the surface of parts produced by FDM of the post process using a vibratory mass finishing vibratory machine is presented. For the surface assesment, the technique of X-ray computed tomography was employed. The FDM part was manufactured with PC (Polycarbonate), a

Stratasys Fortus 400 machine with a T16 nozzle tip and PC-S support material was used for the test.

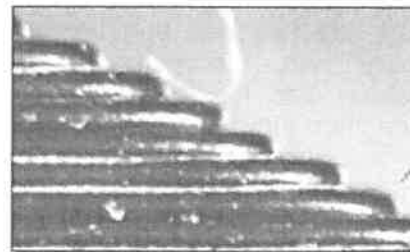


FIGURE 1. Stair stepping effect [3]

BACKGROUND

In order to enhance the surface finishing of FDM parts, secondary post-process techniques are carried out. These techniques are divided into three categories: computer numerical control (CNC) machining, chemical methods and mass finishing (MF) [4].

Mass finishing is also called loose abrasive finishing. Firstly, this technology was designed to process metal parts and consists in placing the part in a deburring machine where finishing is carried out on the most exposed surfaces as well as on the edges of the parts. MF has been used to finish FDM parts; in fact, Stratasys ([6]) suggests the use of vibratory and centrifugal barrel mass finishing to abrade away layer marks. Boschetto et al. [4] used the barrel finishing technique to improve surface roughness obtaining average roughness values between 3 and 7 μm measured with a profilometer [4].

X-ray computed tomography is a non-destructive test based on the measurement of different absorption coefficient of the materials crossed by a penetrating beam such as an X-ray [3]. This technology is able to measure both the inner and outer geometry of a component without need to cut it through and destroy it. Also, it is the only technology for industrial quality control of workpieces having nonaccessible internal features or multimaterial components [7].

The aim of this work is to show some results of non-destructive CT inspection applied to devices manufactured by FDM technology and processed in a mass finishing machine in order to quantify the decrease in size of the filament versus different post-process times using mass finishing and to inspect to what extent this process affects the outer and inner filaments of a part built by FDM.

MATERIALS AND METHODS

A part with a cylindric shape was designed as shown in Figure 2a. In order to understand the impact of mass finishing process on external filaments, the part was built considering four sections with different manufacturing parameters. The top section has a sparse structure (this structure was regarded as the base and it was not considered for the present study) and each consecutive section adds a different configuration of number of outer contour filaments: section two adds one contour, section three adds three contours and section four adds five contours. The proposed part, showing the different sections to asses, is shown in Figure 2b, whilst Figure 2c shows the built configuration on each section.

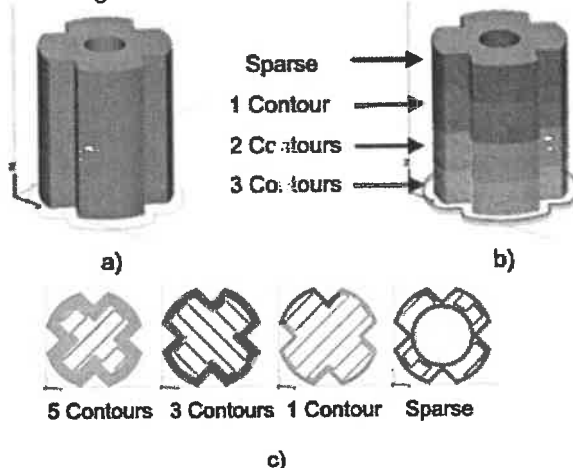


FIGURE 2. a) Image of the FDM part b) Manufactured device c) Contours of the designed device

The part was manufactured using a Stratasys Fortus 400 machine loaded with PC, PC-Support and with a T16 nozzle. Stratasys Fortus Insight v10.1 software was used for controlling the manufacturing configuration parameters. Figure 3 shows the manufactured part.

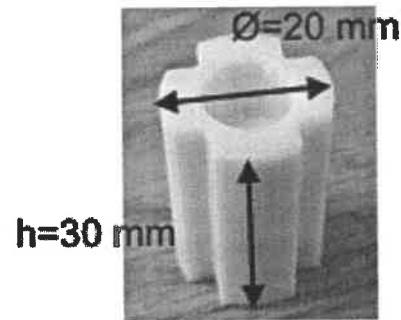


FIGURE 3. Image of the built device.

A 240/470, 3-phase, 60 cycle-motor (Giant, USA) vibratory finishing machine was employed to carry out the finishing operation. Triangular ceramic media 1 1/4" height and 1 1/8" base has been used, with a green tip in order to obtain a ratio of 48:1 of final concentration compound liquid.

The part was processed according to Boschetto specified time intervals [4], for 960 minutes of total mass finishing process, the cylindrical device was analyzed in a mounting progression as shown in Figure 4a.

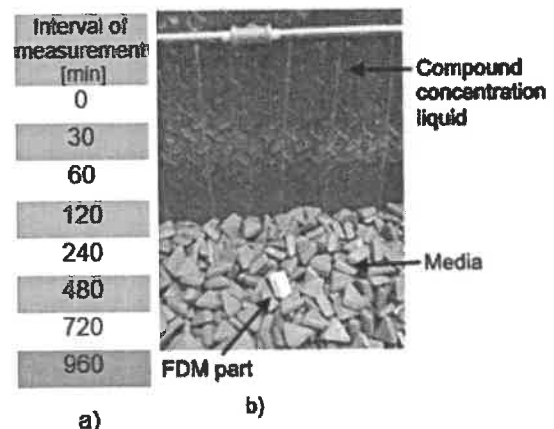


FIGURE 4. a) Interval of measurement. b) Giant vibratory finishing machine

The outer filaments of the part manufactured by FDM were studied by means of a Nikon Metrology XT H225ST CT system with the following parameters: 90 KV, 11.7 W, exposure time of 267 ms, and 3142 images (Figure 5).

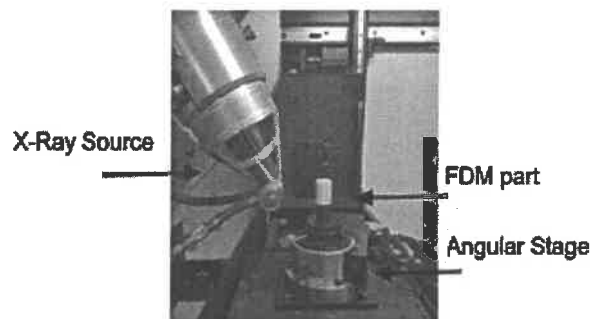


FIGURE 5. Set up to assess the outer filaments of the FDM part using X-ray CT equipment

TESTS AND RESULTS

The FDM part was inspected after each interval shown in Figure 4a by means of X-Ray CT in order to determine the wear of the external filaments. Figure 6a shows a section view obtained with the CT.

The external filaments of the FDM part were analyzed as shown in Figure 6b. Mean height of the roughness profile was obtained by measure the distance from the peak to the valley, i.e, the amplitude formed by adjacent filaments, according to the Figure 7. Ten measurements, on the order of microns, were taken for each of the three sections considered in this study.

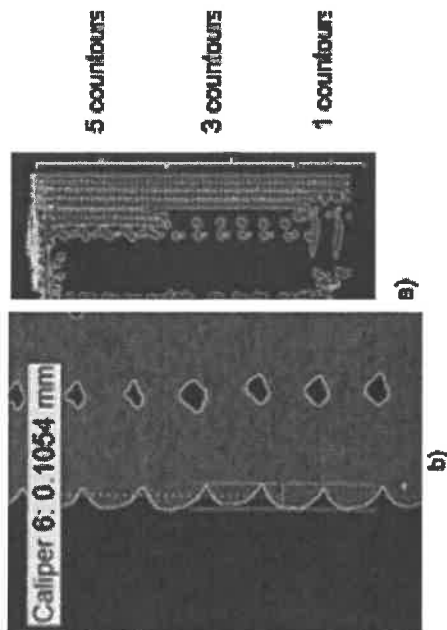


FIGURE 6. a) Sectional view of PC cylinder; b) measurement taken from CT data for five-countour section at thirty minutes of mass finishing process

$$Rc = \frac{1}{m} \sum_{i=1}^m Z_{ti}$$

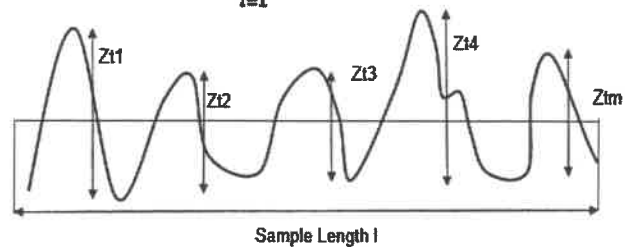
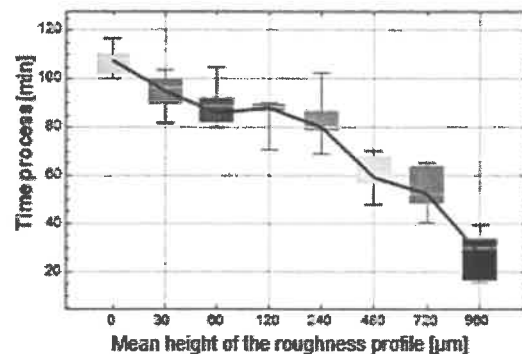
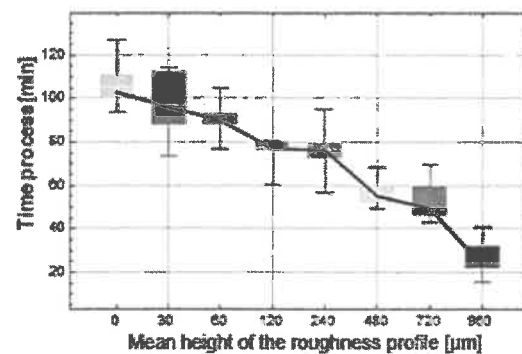


FIGURE 7. Mean height of the roughness profile elements Rc in a sampling length

In order to track the decrease of the valley-to-peak distance in the course of time, measurements were analyzed through *box whiskers* using Wolfram Mathematica 10.0 Student Edition. Table 1 shows the mean roughness value for each section and its standard deviation. Figure 8 shows the box-whisker graphics for each of the analyzed sections.



a)



b)

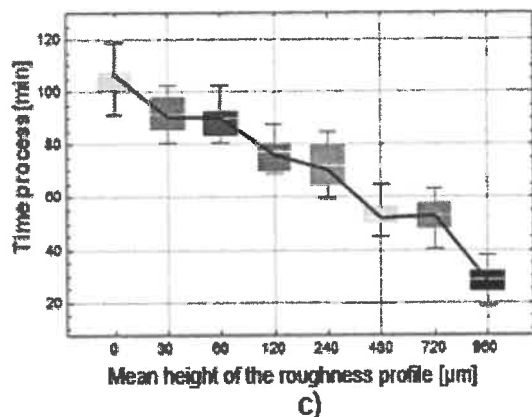


FIGURE 8. Box-whisker graphics for measurements of peak-to-valley outer contours: a) one contour; b) three contours; c) five contours.

TABLE 1. Mean roughness value and standard deviation for one-, three- and five-countour data

Interval [min]	1-contour section		3-contour section		5-contour section	
	$\bar{x}^*$	σ^{**}	$\bar{x}$	σ	$\bar{x}$	σ
0	107.75	5.28	106.69	9.42	104.71	7.38
30	94.9	6.94	97.97	13.15	91.7	7.28
60	88.91	7.6	90.25	8.67	89.89	6.86
120	86.1	6.23	75	7.79	76.42	5.9
240	94.05	10.63	76.16	9.61	72.68	9.22
480	60.07	7.33	56.58	6.1	53.35	5.72
720	54.43	8.8	52.94	8.77	52.42	7.19
960	27.45	8.99	26.63	8.04	28.25	5.55

* $\bar{x}$ = Mean value [μm] ** σ = Standard deviation [μm]

DISCUSSION

Figure 8 shows how roughness decreases throughout time. The three sections display the same behavior throughout the mass finishing process.

After eight hours of applying the mass finishing process, the amplitude is reduced in almost fifty percent, whereas sixteen hours of mass finishing process are required to achieve eighty percent of reduction. It should be noted that the

amplitudes of interest do not disperse when the post-process is elapsed. This can be seen in the standard deviation values depicted in Table 1. On the other hand, it was possible to assure that applying sixteen hours of mass finishing post process only affects the outer contours, no matter how many of them. Figure 9b shows that the outer contour was the only one smoothed.

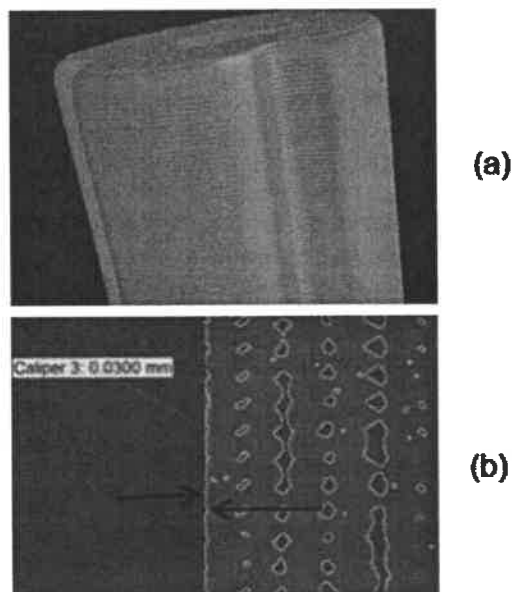


FIGURE 9. a) CT view of the device after 960 minutes of mass finishing process; b) measurement of amplitude after 960 minutes of mass finishing process; the white arrow indicates the length of the outer contour.

CONCLUSIONS

The stair stepping effect is one of the major disadvantages of the FDM technology; nowadays, there are several post-treatment processes intending to minimize this disadvantage. Nevertheless, it has not been discussed to what extent these processes affect the inner layers.

This work shows different results related to the wear of the outer filaments of a part designed and manufactured by FDM as result of being processed in a mass finishing machine, Boschetto progressing time for barrel finishing was employed with the objective of having known intervals to study mass finishing; for our study, vibratory machine results did not have the behavior reported in [4] since the technologies employed are different.

Inspecting the images obtained from CT data, it was found that the time employed in this experiment did not affect the inner layers; however, the designer must take into account the decrease of size of filaments when a post treatment of mass finishing is needed.

ACKNOWLEDGEMENTS

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CORRELATION BETWEEN BUILDING PARAMETERS, MECHANICAL PROPERTIES AND BUILDING TIME IN MANUFACTURED PARTS BY FDM

Leopoldo Ruiz-Huerta¹, A. Horacio Gutiérrez-Osorio², Alberto Caballero-Ruiz¹ and Vicente Borja³

¹Laboratorio Nacional de Manufactura Aditiva, Digitalización 3D y Tomografía Computarizada (MADiT)

Centro de Ciencias Aplicadas y Desarrollo Tecnológico (CCADET)

Universidad Nacional Autónoma de México (UNAM)

Circuito Exterior S/N, Ciudad Universitaria AP 70-186, C.P.

04510, Ciudad de México, México

² Programa de Maestría y Doctorado en Ingeniería, Universidad Nacional Autónoma de México, Ciudad de México, 04510, México.

³Centro de Diseño Mecánico e Innovación Tecnológica, Facultad de Ingeniería, Universidad Nacional Autónoma de México, Ciudad Universitaria, C. P. 04510, Ciudad de México, México.

leoruiz@unam.mx

ABSTRACT

This paper describes the effect that building parameters (layer thickness, raster width, raster angle, air gap and part orientation) have on the mechanical properties and building time of parts manufactured by Fused Deposition Modelling (FDM). The authors used the Insight® software to observe the influence of building parameters on building time. The results of the analysis reported in this paper show that building parameters affect the tensile strength and the building time of parts. The obtained building time was correlated with building parameters and mechanical properties reported in [1-4] to finally obtain the correlation between the building parameters, mechanical properties and building time.

BACKGROUND

Additive Manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, in contrast to subtractive manufacturing methodologies. Additive manufacturing processes are classified within seven categories: material extrusion, material jetting, binder jetting, sheet lamination, vat photo-polymerization, powder bed fusion and direct energy deposition. Each one of these processes has different associated technologies

according to its specific technological performance characteristics [Standard ASTM F2792 - 12th].

FDM technology belongs to the material extrusion process category and, according to the Wohlers Report 2015, represents 23% of the industrial sector of additive manufacturing [5]; for this reason, it is important to study this manufacturing technology from the perspective of the building parameters in order to understand its behaviour when they change, affecting the final characteristics of the part.

There are several works that study the variation of mechanical properties of parts manufactured by FDM depending on the process parameters (building parameters). It has been demonstrated that part orientation plays an important role in the tensile strength [6]. Also, the size of the filaments is determinant in mechanical strength, since smaller filaments affect the tensile strength when arranged in particular directions, while larger filaments behave differently [7].

In general, building parameters, such as raster width, layer thickness, angle raster, air gap, and building orientation (part orientation) are determinant factors in mechanical properties

resulting from parts manufactured by FDM technology [1], [2], [7], [8] and [9]. The inner structure of a construction geometry represented with the software Insight® coincides with the internal structure of a part manufactured by FDM and, with the use of this software, it is possible to obtain the building time of fabricated parts in accordance to building parameters [8].

From the fact that the variation of building parameters directly affects the mechanical properties of the parts, the aim of the work reported in this paper is to identify the correlation between the mechanical properties, the size of filaments and the building time of parts manufactured by FDM. This using ABS (Acrylonitrile Butadiene Styrene) as building material and the properties established previously by Godfrey C., et al., Montero, M., et al., Alhubail et al., and Panda et al. [1 - 4].

METHODOLOGY

The building parameters analysed in this study were *layer thickness* (LT), *part orientation*, *raster angle*, *raster width* (RW) and *air gap* [1]. *Size of filaments* (SF) refers to the size of the cross-section of each filament; in [9], the cross-section of the filament is geometrically modelled as an ellipse. For practical purposes, in this study, *size of filament* is defined as the product of the raster width by the layer thickness.

$$SF = (RW) (LT) \quad (1)$$

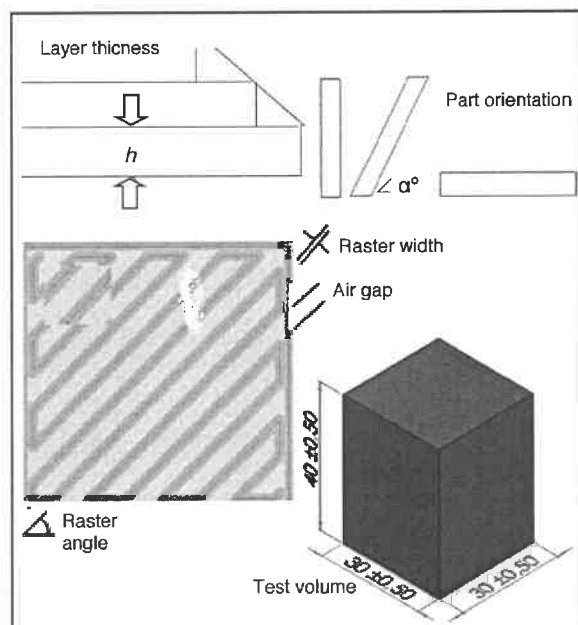


FIGURE 1. Building parameters and testing volume.

ABS (Acrylonitrile Butadiene Styrene) has been selected as building material as established in [1-4]. The analysis is based on data obtained from tables of Design of Experiments (DOE) by the authors of references [1-4].

A testing volume (30 x 30 x 40 mm) was designed with Solidworks® CAD software and then it was exported as an STL format file to Insight® software to determine building time (Fig. 1).

The next steps were followed to obtain the building time of the testing volume:

- Four tables of DOE reported in [1-4] were reviewed; in [1] and [3], a Stratasys Fortus 400mc machine was used; in [2], a Stratasys FDM 1650; and in [4], a FDM Vantage SE. Building parameters of each table of DOE have different values, levels and number of experiments. For all of the data tables of the above references, except [2], the raster angle was alternated layer by layer so that the filaments of the antecedent layer were orthogonal to those of the subsequent layer. The raster angle between layers is constant in [2].
- The following parameters were taken from data tables: experiment number, air gap, raster width, layer thickness, raster angle, part orientation and tensile strength.
- Using the building parameters data of each experiment, Insight® was employed to calculate the building time of the testing volume.
- Size of filament was calculated using Equation (1) for each experiment.
- With data complete, an analysis to identify the relations between tensile strength, building time and size of filaments was performed, according to the variation of the building parameters involved.

RESULTS

The next relations were found through data analysis.

NOTE: σ is the standard deviation.

Relation 1. Building time vs. raster angle.

Fixing air gap, part orientation and size of filaments; the building time increases when the raster angle changes from 0° to 45°.

For example, for a given group of parameters, the green bar in Fig. 2 represents the building time when the testing volume is manufactured with a raster angle of 0°, while the orange bar represents the time increment when manufacturing the same part with the same building parameters but with a raster angle of 45°.

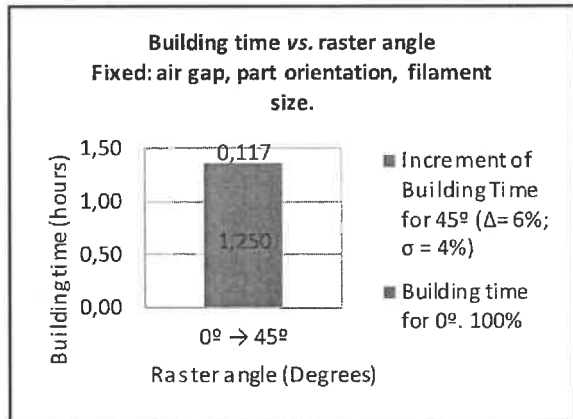


FIGURE 2. Relation 1.

Relation 2. Tensile strength vs. raster angle. Case I.

For negative air gap, fixing: air gap, part orientation and size of filaments; the tensile strength increases when the raster angle changes from 0° to 45°.

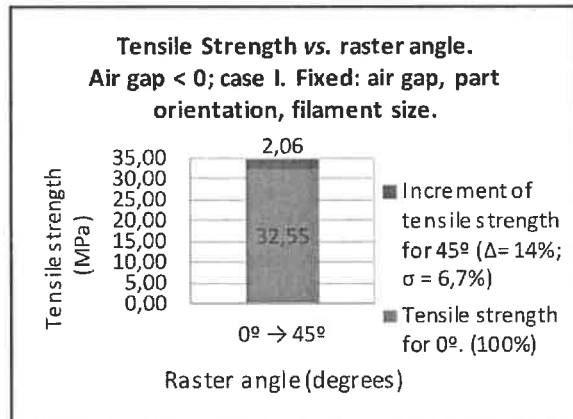


FIGURE 3. Relation 2, case I.

Relation 2. Tensile strength vs. raster angle Case II.

For positive and zero air gap, fixing air gap, part orientation and size of filaments; the tensile strength decreases when the raster angle changes from 0° to 45°.

Figs. 3 and 4 are examples of relation 2: cases I and II. For a given group of parameters, the blue

bar represents the tensile strength when the testing volume is manufactured with a raster angle of 0°, while the red bar represents the increment (in Fig. 3) and decrement (in Fig. 4) of the tensile strength when manufacturing the same part with the same building parameters but with a raster angle of 45°.

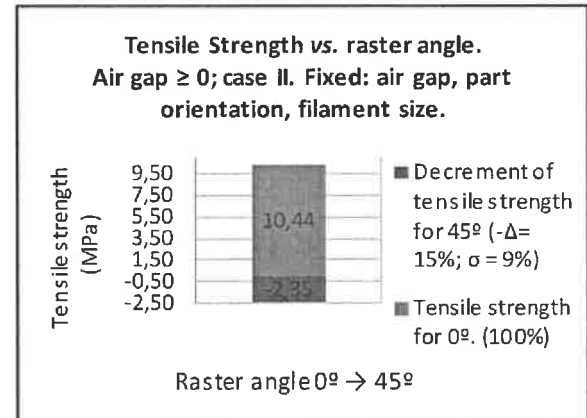


FIGURE 4. Relation 2, case II.

Relation 3. Building time vs. part orientation.

Fixing air gap, raster angle and size of filaments; the building time increases when the part orientation changes from 0° to 90°.

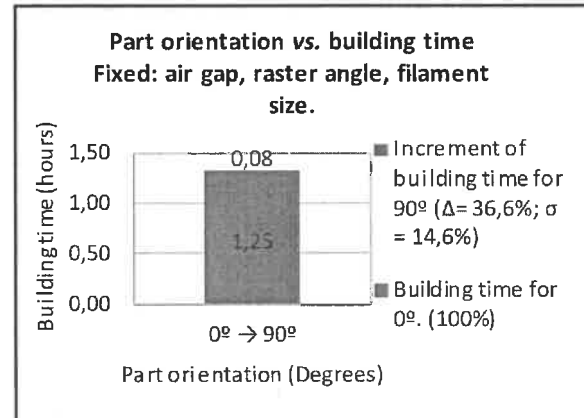


FIGURE 5. Relation 3.

Fig. 5 is analogous to Fig. 2, but the part orientation varies.

Relation 4. Tensile strength vs. part orientation. Case I.

Fixing air gap, raster angle and size of filaments; the tensile strength decreases when the part orientation changes from 0° to 90°.

Fig. 6 is analogous to Fig. 4, but the part orientation varies.

Relation 4. Tensile strength vs. part orientation. Case II.

Fixing air gap, raster angle and layer thickness; the tensile strength decrement is smaller for thick filaments than for thin filaments, when the part orientation changes from 0° to 90°. Observe the decrement shown in Table 1.

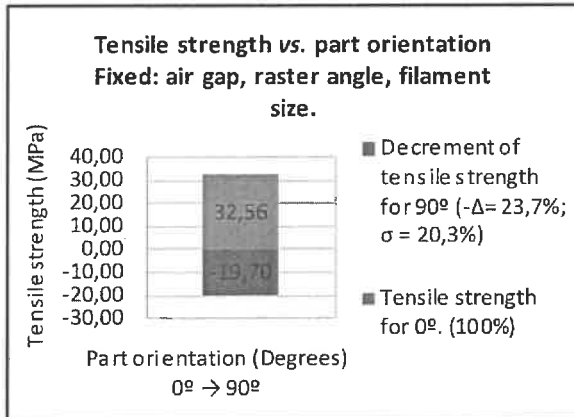


FIGURE 6. Relation 4, case I.

TABLE 1. Relation 4, case II.

Run	Layer thickness, [mm]	Part orientation [°]	Raster angle [°]	Raster width [mm]	Air gap [mm]	Tensile strength [Mpa]	Cross-section of filament, size (cm²)	Decrement of tensile strength
1	0,1270	0	0	0,2032	-0,00254	32,56	0,026	
9	0,1270	90	0	0,2032	-0,00254	12,86	0,026	60,50%
3	0,1270	0	0	0,5588	-0,00254	24,81	0,071	
11	0,1270	90	0	0,5588	-0,00254	23,55	0,071	5,08%
17	0,3302	0	0	0,4572	-0,00254	31,46	0,151	
25	0,3302	90	0	0,4572	-0,00254	20,55	0,151	34,68%
19	0,3302	0	0	0,9652	-0,00254	24,99	0,319	
27	0,302	90	0	0,9652	-0,00254	24,72	0,319	1,08%

Relation 5. Building time vs. size of filaments.

Fixing air gap, raster angle and part orientation, building time decreases when the size of filaments increases.

For instance, the curve shown in Fig. 7 is formed by a group of points (with the same fixed parameters), which represents the building time of the testing volume, but only varying the size of filaments. If the size of filaments is changed

for other group of fixed parameters, a similar curve is obtained; it means that this phenomenon is the same.

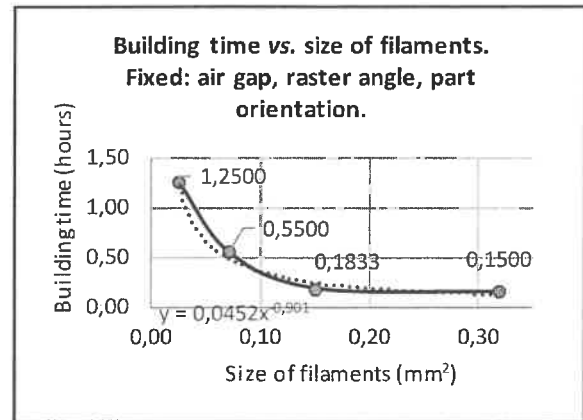


FIGURE 7. Relation 5.

Relation 6. Tensile strength vs. SF. Case I.

Fixing air gap, layer thickness, raster angle and part orientation; for negative and zero air gap: if the part orientation is 0°, the tensile strength decreases when the size of filaments increases.

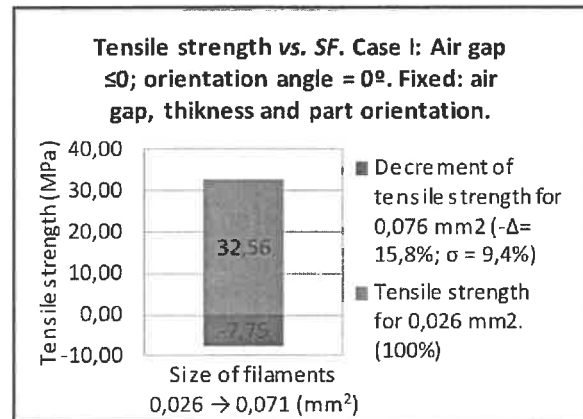


FIGURE 8. Relation 6, case I.

Relation 6. Tensile strength vs. SF. Case II.

Fixing air gap, layer thickness, raster angle and part orientation; if air gap is negative or zero but part orientation is 90°, the tensile strength increases when size of filaments increases.

Relation 6. Tensile strength vs. SF. Case III.

Fixing air gap, layer thickness, raster angle and orientation part; if air gap is positive, the tensile strength increases when the size of the filaments increases; even though the part orientation changes.

Figs. 8, 9 and 10 show examples of relation 6, cases I, II and III. For a given group of parameters: the blue bar represents the tensile strength for thin filaments, while the red bar depicts the decrement (in Fig. 8) and increment (in Figs. 9 and 10) of the same mechanical property (with the same group of parameters) for thick filaments.

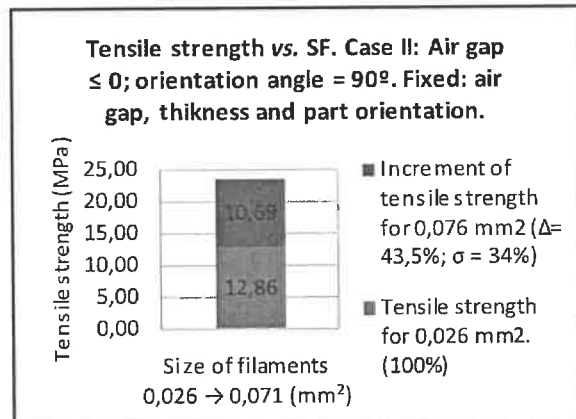


FIGURE 9. Relation 6, case II.

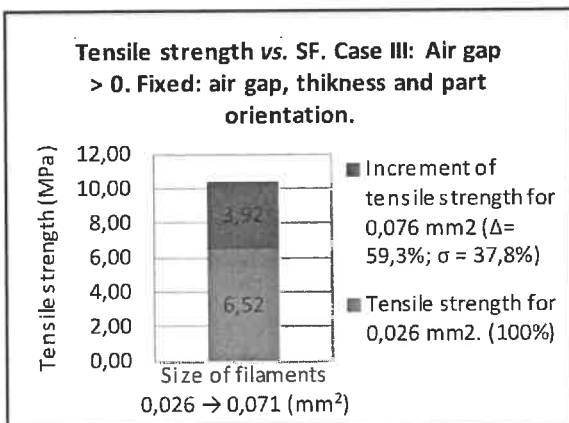


FIGURE 10. Relation 6, case III.

Relation 7. Tensile strength vs. SF.

For negative and zero air gap; fixing air gap, raster angle and part orientation; if the tensile strength is constant (within a range of $\pm 10\%$), the building time decreases when the size of the filaments increases.

Fig. 11 is analogous to Fig. 7.

DISCUSSION

The graphs are meant to show, through an example, the phenomena that occur when an input parameter is changed and others are fixed.

Table 2 summarizes the relations, which show the effect (output) on the tensile strength and building time of changing a parameter from a value to another one (input). For this reason, relations 1, 3 and 5 were omitted because they are implicit in relations 2, 4 and 6, respectively.

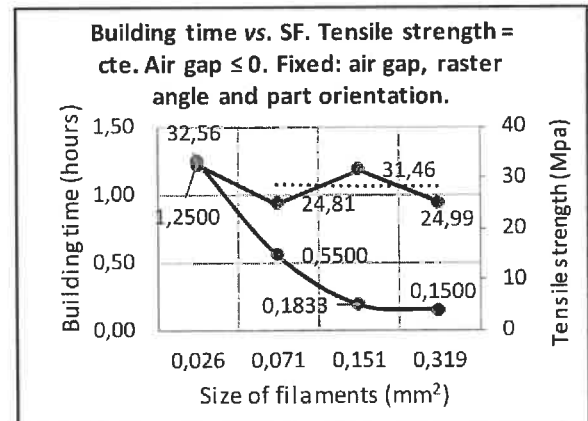


FIGURE 11. Relation 7.

TABLE 2. Summary of relations. FX = Fixed; D = Depends on LT and FS; → It changes to; ↑ It increases; ↓ It decreases; C=Case.

Relation	Layer thickness	Air gap	Raster angle	Part orientation	Size of filament	Tensile strength	Building Time	Tensile strength (Mpa)	Building time (hours)
2, C-I	D	FX < 0	0° → 45°	FX	FX	↑	↑	32,56 ↑ 34,61	1,25 ↑ 1,36
2, C-II	D	FX ≥ 0	0° → 45°	FX	FX	↓	↑	10,44 ↓ 8,09	0,43 ↑ 0,46
4, C-I	D	FX	FX	0° → 90°	FX	↓	↑	32,56 ↓ 12,86	1,25 ↑ 1,33
6, C-I	FX	FX ≤ 0	FX	FX = 0	↑	↓	↓	32,56 ↓ 24,81	1,25 ↓ 0,55
6, C-II	FX	FX ≤ 0	FX	FX = 90	↑	↑	↓	12,86 ↑ 23,55	1,33 ↓ 0,70
6, C-III	FX	FX > 0	FX	FX	↑	↑	↓	6,52 ↑ 10,44	0,48 ↓ 0,33
7	D	FX ≤ 0	FX	FX	↑	FX (± 10%)	↓	28,45	1,25 ↓ 0,15

Input Output Example

Additionally, Table 2 contains two columns of data (tensile strength and building time) in order to give an example for each relation. These data can be observed in the figures as well. As it can be observed in relation 2, C-I, and relation 6, C-I, negative air gap, orientation part of 0° and raster angle of 45° give the best tensile strength (34.61 MPa). Relation 2, C-2, shows that a

positive air gap decreases the tensile strength (10.44 MPa, with respect to 32.56 MPa of relation 2, C-I) as well as with positive air gap, varying the raster angle from 0° to 45°, a decrement of the tensile strength is obtained (from 10.44 MPa to 8.09 MPa). The change of part orientation from 0° to 90° (relation 4, C-I) is the cause of the decrement of the tensile strength (from 32.56 MPa to 12.86 MPa). Relations 6, C-I and C-II, describe that for negative and zero air gap, the decrement of the tensile strength is shorter for a part orientation of 0° than the increment of the tensile strength for a part orientation of 90° when increasing the size of the filaments (varying raster width and fixing layer thickness), whereas that decrement of building time decreases almost 50% for both cases. Relation 6, C-III, demonstrates that it is possible to get an increment of the tensile strength and a decrement of the building time for parts with positive air gap if the size of the filaments is increased; this does not imply that a tensile strength similar to the tensile strength of a part with negative air gap can be obtained.

Finally, these relations can be considered for FDM technology-related design, manufacturing or research; for instance, relation 7 states that if thick filaments are selected, then a shorter building time will be obtained (with a similar tensile strength) than with thin filaments. This directly affects the manufacturing cost.

CONCLUSIONS

From the data in the references, supplementary data obtained from Insight® software to determine building time, and from the application of Equation (1) to determine filament size, some relations have been found which describe the tensile strength and building time behaviour of parts manufactured by FDM, considering the changes of the building parameters. More experiments with different data are needed in order to find out what would happen when having other inputs different to those shown in the found relations, but this work is a baseline for further research on other aspects of this subject.

ACKNOWLEDGEMENTS

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Computed Tomography aided porosity comparison between ABS Filaments and FDM Manufactured Pieces

Leopoldo Ruiz Huerta*¹, Adriana Hernández-Contreras², Alberto Caballero-Ruiz¹ and Yara Cecilia Almanza-Arjona¹

¹Laboratorio Nacional de Manufactura Aditiva, Digitalización 3D y Tomografía Computarizada (MADiT)

Centro de Ciencias Aplicadas y Desarrollo Tecnológico (CCADeT)

Universidad Nacional Autónoma de México (UNAM)

Circuito Exterior S/N, Ciudad Universitaria AP 70-186, C.P.

04510, Ciudad de México, México

²Programa de Maestría y Doctorado en Ingeniería, Universidad Nacional Autónoma de México, Ciudad de México, 04510, México.

Email leorui@unam.mx

ABSTRACT

The aim of this study is the comparison of the porosity of two different material stages used in the FDM technology, which are the bulk material (canister) and the extruded material.

The pieces manufactured by FDM are constructed by the extrusion of filaments creating thin layers; these filaments contain pores in its internal structure. These pores are analyzed by means of a non-destructive test, the CT. There are other voids generated due to the deposition process of filaments (e. g. space between them), but are not in the scope of this study.

CT scans were performed to samples in order to analyze and compare the porosity of the filaments in the two stages of interest. The total porosity and pore size of each sample were observed and calculated using Volume Graphics™ software.

INTRODUCTION

Additive Manufacturing (AM), also known as rapid prototyping, can be defined as the manufacturing process of three-dimensional solids by means of joining several thin layers of material [1]. In general, this kind of process can be subdivided in to seven categories, e.g., Lamination, Selective Laser Melted, Stereolithography, etc., attending on the method used to join each layer, and the

employed material. An outstanding characteristic of the AM is that all of the information necessary to manufacture any piece is contained in a digital file (STL file), and no further removal processes are required.

From the broad range of available AM methods, the technology known as Fused Deposition Modeling (FDM) has been one of the most successful technologies in the industry since its introduction in late 1980's by Stratasys Inc. [2], mainly due to its simplicity. The process comprises the heating of a polymer material up to its melting point temperature, and its extrusion through a nozzle to generate thin layers. These filaments are deposited to make a horizontal layer with the aid of a cartesian robot or similar. To produce a particular shape, one layer is added on the top of the previous one to construct a solid, slice by slice, as is indicated by the STL file [3].

The high application of FDM technology within industry, makes the analysis of mechanical properties crucial to characterized the pieces manufactured by this process [4]. A key property of the finished parts is the porosity, since it can affect their mechanical properties. Ang and co-workers [5] have reported that the presence of air pores in FDM filaments can be a source for fractures, when the piece is subject of tensile strength.

Previous studies showed that the mechanical properties were affected not only by the voids generated by the same technology, but also by the pores contained within the scaffolds of the piece, the higher the porosity the lower mechanical strength [5].

The formation of air voids in parts manufactured by FDM, comes from the variation of construction parameters such as airgap, raster width and raster angle. The presence of porosity is mainly located in areas where there is no overlapping between filaments or where abrupt changes in the direction of material deposition occur [6].

Several authors found that the rupture of pieces built by other AM technologies that employ metal powder such as Selective Laser Melting (SLM) process starts in a pore [7],[8].

From these results, it is possible to suggest that the higher the porosity, the higher the probability of failure in the piece.

For the same process, the porosity has been observed and quantified by visual inspection with scanning electron microscope and Computed Tomography (CT) [7]. These results aid to relate the porosity of the sample with the mechanical properties of the manufactured pieces and the possible location of failure.

Computed tomography analysis is an attractive technique to study AM-manufactured items, since it is not necessary to destroy the sample. The use of this tool is classified as a non-destructive test which allows to observe its internal structure without altering the piece [9].

This method allows to see density changes in the material using X-rays at different intensities [10]. Computed tomography generates an image where is it possible to observe the internal structure of the material, in particular, the existence of voids and pores, their shape, distribution and connectivity [12], [11]. The aim of this work is to measure the density of pores inside of two samples, representing two different stages of the building material: the canister filament and the rasters in the final pieces. Computed

Tomography was employed to find a relationship between the porosities of each stage and its effect on the mechanical properties of the final pieces.

EXPERIMENTAL LAYOUT

For this experiment, Acrylonitrile Butadiene Styrene M30 (ABS-M30) was analyzed. This material is produced by Stratasys, who adds different additives to increase the mechanical resistance between 25-70 percent with respect to the standard ABS. Additionally, properties such as tensile, flexural and impact strength, and layer bounding are improved [13].

For the purpose of this work, two samples from the same canister of material were studied. The first one was a filament taken directly from the canister without any further treatment. The bulk material filament has a length of 10 [mm], and a diameter of 1.77 [mm].

The second sample was a disk with a diameter of 5 [mm] and a height of 1.25 [mm] produced using a FDM Fortus 900mc machine [14], according to the building parameters shown in TABLE 1. The disk-form was chosen since this geometry gives the same X-ray penetration in all directions.

TABLE 1 FDM construction parameters.

FDM Construction Parameter	Value
Airgap	0 [mm]
Nozzle	T16
Layer height	0.254 [mm]
Raster angle (between layers)	0°
Raster width	0.4064
Layers	5
Manufacturing orientation	0°

The idea was to compare the porosity percentage in both cases; to simplify the comparison, both samples were produced with the same volume. The samples were made sufficiently small to place them close enough to the CT gun so as to obtain the highest resolution given by the CT, and to avoid the bending of the filament (FIGURE 1).

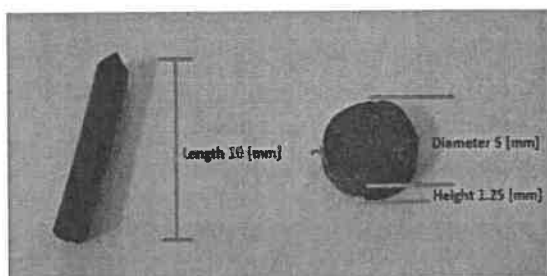


FIGURE 1. Samples dimensions.

The samples porosity was measured using a Nikon XT H 225 ST Tomography [15]. The CT parameters are shown in TABLE 2.

TABLE 2. CT analysis parameters.

Parameter	Value
Voltage	120 [kV]
Current	73 [μ A]
Time	1000 [ms]
Projections	3142
Frame per Projections	2

After the CT scans were performed, the data obtained was processed and projections were reconstructed using the Volume Graphics™ software VGStudio Max 2.2 [16]. For both pieces, surface determination was set in automatic. In this configuration, the software estimates the locations of the material and the air. The starting contour healing was set to remove all noise particles found in a distance of 0.0255 [mm]. This was done to eliminate unwanted particles that were present in the current volume of each piece. The density threshold can be appreciated in FIGURE 2.

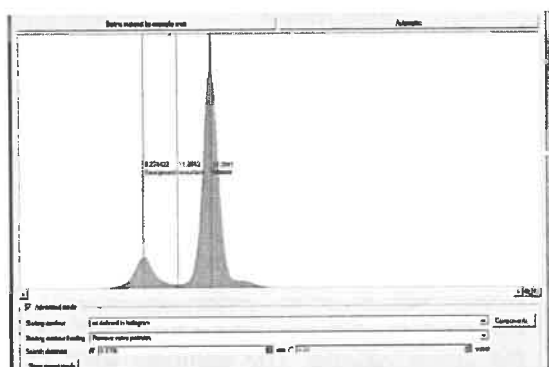


FIGURE 2. Surface determination parameters

As a reference for the pore size, the first analyzed piece was the filament. The results are reported in Analysis 1. For both pieces, a defect detection analysis was performed to

find their porosity. The configuration parameters for the defect detection can be found in TABLE 3. The parameters were the same for both pieces, except the void max diameter. For the filament, the void max diameter was set in 1.5 [mm] to have a large spectrum of pore sizes. The largest pore size found in the filament then was used to set the void max diameter parameter for the disk analysis. The results of the defect detection analysis for the disk are presented in Analysis 2.

TABLE 3. Defect detection parameters

Parameter	Value
Analysis mode	Voids
Void max diameter	1.5 [mm]
Noise reduction	Low
Probability criterion	General
Analysis area	Internal Cleaning Small
Surface scaling	Off

RESULTS

The resulting data from the porosity analysis contains the porosity percent, pore diameter, pore volume, and the number of pores in different sizes. In the filament analysis it was found a maximum pore diameter of 0.4116 [mm], and a minimum of 0.016 [mm]. On one hand, the total porosity percentage of the bulk filament was 4.89 %, while in the disk it was 3.74% which represents a decrease of about 30% in the porosity. Under the hypothesis that the pore size in the manufactured piece is smaller than the one found in the bulk material, the void max diameter was set to 0.4116 [mm] in the defect detection for the disk.

Analysis 1: Bulk filament

In FIGURE 3 a) the number of pores vs volume distribution can be seen. It was found that the pore volume with the highest count was 0.0000057 [mm³], with a total number of 12000 pores in the whole filament. Also, FIGURE 3 a) shows that the pores are concentrated between 0.000001 [mm³] and 0.000020 [mm³], making a smooth curve. FIGURE 3 b) exhibits that most of the pores have a diameter between 0.05 [mm] and 0.38 [mm], and are concentrated in the middle of the range.

FIGURE 3 c) illustrates a longitudinal section of the filament where it is possible to appreciate the pores.

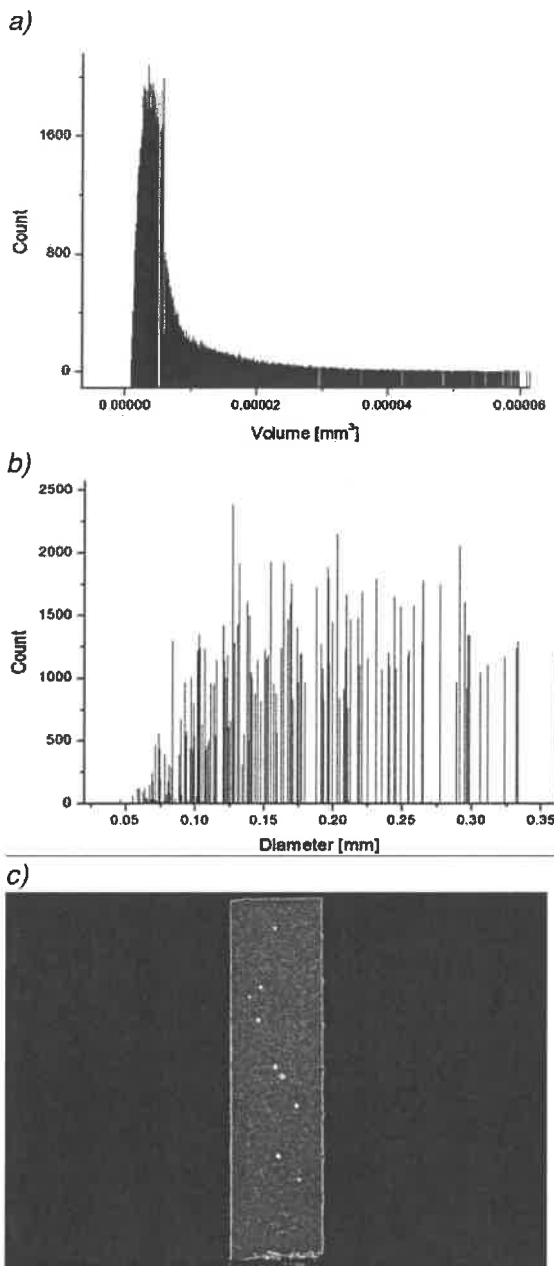


FIGURE 3. a) Count – Volume graph of analysis 1 b) Count – Diameter graph of analysis 1 c) View of pores in filament.

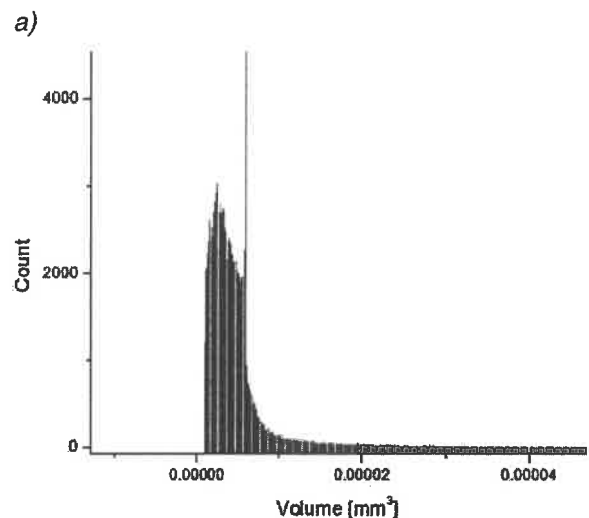
Analysis 2: Disk analysis

In this case the pore volume with the greatest count were, again, 0.0000057 [mm³] with 13500 pores. Clearly, the pores are concentrated between 0.000001 and 0.000006 [mm³] (FIGURE 4 a). Pore diameter is distributed between 0.012 [mm] and 0.3982 [mm].

Porosity comparison between the filament and the disk.

The pore distribution in the bulk filament is practically uniform (FIGURE 3 b) whereas in the disk the distribution of the pores is concentrated on left side of the graph (FIGURE 4 b). This phenomenon can be associated to the FDM nozzle.

FIGURE 3 c) and FIGURE 4 c) show the traversal section of the filament and the disk respectively. The pore size diameter is more homogeneous in the disk than in the filament. However, in the disk it can be seen a very large void which can be associated to space between filament rather than a pore itself.



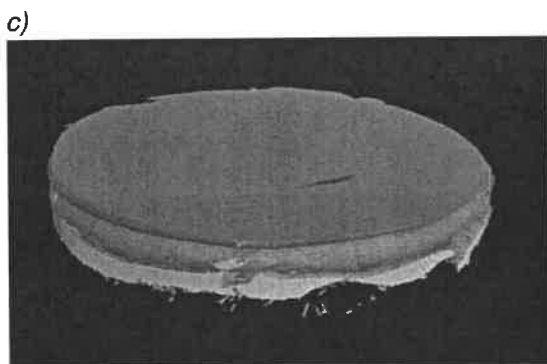
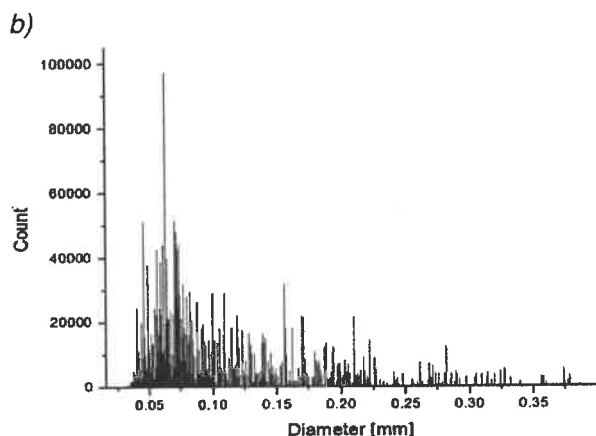


FIGURE 4. a) Count – Volume graph of analysis 2 b) Count – Diameter graph of analysis 2 c) View of pores in the disk a very large space between filament can be seen.

CONCLUSIONS

Comparing the pore size distribution between the bulk material filament and the extruded piece, it was found that the bulk filament contains a homogeneous pore size whereas the disk contains a higher proportion of small pores (around 0.06 [mm]). In the filament, the pores diameter size was distributed in a range from 0.016 to 0.4116 [mm], whereas in the disk this range was from 0.012 to 0.3982 [mm], which represents a slight reduction. We can infer a resize of the pores diameter due to the extrusion through the 0.254 [mm] nozzle. The extrusion not only reduces the pore size, but makes it more homogeneously distributed in the piece.

CT analysis of the samples gives valuable information regarding the pore size in the filament, however it is not possible to distinguish between pores and voids induced by the space between filaments in the

extruded piece. This difficulty arises since the space between filaments is comparable in size with the pores found in the filament.

It is necessary to remark that this results were obtained for a particular case. To be able to generalize the observed effects, more experiments are required using different manufacturing parameters, materials, and nozzles. Also, it is important to note that the computed tomography is a not standardized inspection tool.

ACKNOWLEDGMENT

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Raster analysis and mechanical behavior prediction by FEM of FDM process

Leopoldo Ruiz-Huerta¹ *, Luis Sánchez-Balazar², Alberto Caballero-Ruiz¹,
Fernando Velázquez-Villegas³

¹Laboratorio Nacional de Manufactura Aditiva, Digitalización 3D y Tomografía
Computarizada (MADiT)
Centro de Ciencias Aplicadas y Desarrollo Tecnológico (CCADET)
Universidad Nacional Autónoma de México (UNAM)
Circuito Exterior S/N, Ciudad Universitaria AP 70-186, C.P.
04510, Ciudad de México, México

² Programa de Maestría y Doctorado en Ingeniería, Universidad Nacional
Autónoma de México, Ciudad de México, 04510, México.

³CIA, Centro de Ingeniería Avanzada, Universidad Nacional Autónoma de México,
Facultad de Ingeniería, Cd. Universitaria, C. P. 04510, Coyoacán, Ciudad de
México.
leorui@unam.mx

ABSTRACT

The present work investigates by FE analysis how the bonding area between filaments of the same layer (intra-layer bonding) and filaments of successive layers (inter-layer bonding) affects the Young's modulus of parts made by FDM process. A straight contact area between filaments is considered and a ratio bonding (BR) is proposed. X-ray computed tomography (X-ray CT) images of the parts were obtained to determine the real BR in FDM parts. FEA results show reduction of the Young's modulus of the FDM part in agreement with previous works.

BACKGROUND

One of the major advantages of additive manufacturing (AM) technologies is that, unlike the traditional manufacturing processes (such as tooling, cutting, and milling), the foremost allow fabricating parts with any geometry regardless its complexity [1]; however, AM processes have transformed from prototyping technologies to end-use part processes, thus it is necessary that the mechanical properties of the involved parts meet norms and quality standards to maintain their integrity during the piece lifecycle.

Fused deposition modeling (FDM) is one of the most used technologies associated with material extrusion, which is one of the seven additive manufacturing processes that allow building tri-dimensional physical objects directly from a 3D digital design [2,3]. One of the main disadvantages of the FDM process is that the parts fabricated have shown anisotropic mechanical behavior resulting from the building principle of this technique [1-4]. Several works [2-9] have shown that the mechanical properties of the parts fabricated by FDM process are completely dependent on the arrangement of the

filaments inside the parts (mesostructured) and this is the result of the manufacturing parameters employed in the fabrication of the part. Previous works [4-8] have also studied the influence of several parameters, such as layer thickness, building part orientation in the work chamber, and the layer filling method (raster angle, raster width, raster-raster and raster-contour air gaps), on the mechanical properties of the parts. In their studies, Ahn et al. [2] and Lee et al. [3] showed that building part orientation and raster angle are the principal parameters that cause the anisotropic behavior of parts made by FDM.

Beside the manufacturing parameters, there is an important feature present in FDM parts known as *neck between filaments* [4, 5]. During the solidification process developed in the FDM process, the filaments establish a cross-bonding [4, 5]. The raster width is maintained in the path planning of the extrusion head that the filaments develop a bridge between them and it is due the process of viscous sintering [10]. FDM parts present two kinds of bonding between filaments: the bonding between filaments of successive layers is known as *inter-layer bonding* whereas the bonding between filaments in the same layer is known as *intra-layer bonding*. By experimental and mathematical analysis, Gurrada et al. [10] showed in their study the influence of the bonding contact between the strength of the FDM parts and how the size of the neck depends on the time of coalescence. Li et al. [4] performed a study to analyze the influence of the void density of FDM parts on their elastic constants, void density was determined by the contact length between filaments varying raster-raster gap length, showing that contact length influences the void density and then the

mechanical properties of the parts. The variation of this bonding length depends on several parameters such as raster angle, raster width, filament material and time. In this work, a computational model for bonding the length between filaments has been derived by means of the X-ray CT images of a real bonding.

MATERIAL AND METHODS

Physical sample

Cylindrical specimens of ABSM-30 with 10 mm of diameter and 10 mm of height were manufactured using a FDM Fortus 400mc machine (Figure 1). Table 1 shows the manufacturing setup parameters employed in the construction.



FIGURE 1. Cylindrical sample

TABLE 1. Manufacturing parameters

Parameter	Value
Raster width	0.3048 [mm]
Raster angle	0°
Tip	T12

X-ray computed tomography was used to observe the bonding length between filaments without destroying the sample. CT Nikon XT H 225 ST equipment was employed. The CT setup parameters are shown in TABLE 2.

TABLE 2. Parameters of CT machine

Parameter	Value
Voltage	110 [kV]
Current	277[μA]
Time	500[ms]
Projections	3142
Frame per projections	1

Figure 2 shows the 3D reconstruction of the projections of the sample analyzed. From this reconstruction the bonding lengths between filaments were measured and considered nominal. These lengths are shown in Table 3.

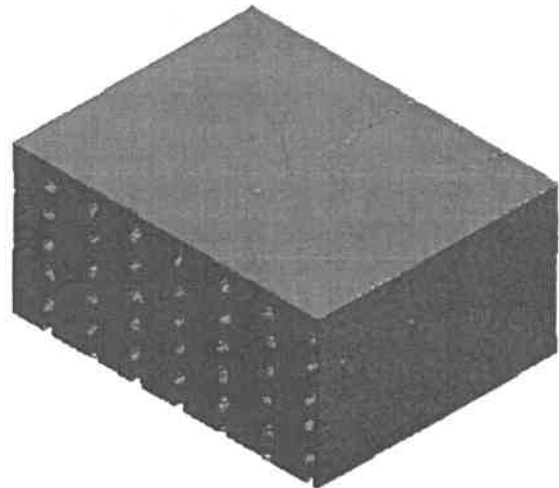


FIGURE 2. 3D reconstruction from CT images

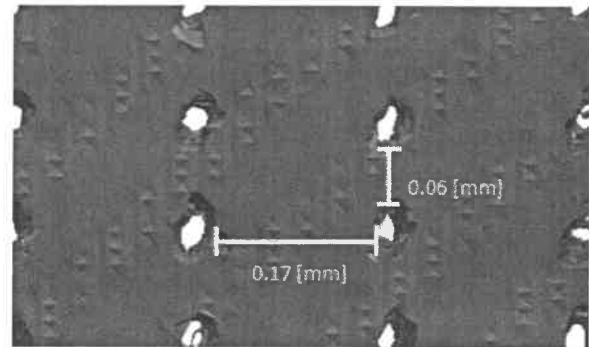


FIGURE 3. Bonding lengths from CT images

TABLE 3. Bonding lengths

Intra-layer bonding length	Inter-layer bonding length
0.06 [mm]	0.17[mm]

Computational details

A finite element analysis was developed to predict Young's modulus of the parts made by the FDM process using Hyperworks Altair FE package.

The analysis was made with the assumption that the filaments were:

- Homogeneous
- Linearly elastic
- Isotropic
- Free of voids

In this paper it is assumed that interphase regions between each filament (of the same layer and of neighboring layers) have the same characteristics as the material filaments, i.e., the

material properties of the interphases keep unchanged (homogenous).

Filament material properties

ABS-M30 was used as filament material. With the assumptions presented above, ABS-M30 is up to 25 to 70 percent stronger than standard ABS and is an ideal material for conceptual modeling, functional prototyping, manufacturing tools and end-use parts. ABS-M30 has greater tensile, impact and flexural strength than standard ABS. Layer bonding is significantly stronger than that of standard ABS, for a more durable part [7].

Table 4 shows the properties of the ABS-M30 from Stratasys data sheet [7]. These properties were used to develop the finite element analysis for all the models considered and correspond to the sample made by the FDM process [7]. Also, the mechanical properties of the filament before and after extrusion by the FDM process were considered to be the same.

TABLE 4. Mechanical properties of ABS-M30 filament

Young's modulus	Poisson's ratio
2230 [MPa]	0.33

Modelling

Unigraphics NX9 CAD software was used to develop all the models mentioned in this work. The first model considered an isolated filament before the extrusion process, which it was assumed as a perfect cylinder with a diameter of 1.778 mm and length of 3.556 mm (see Figure 3a). For this model, the goal was to observe, as a first step, how the mechanical properties changed, i.e., from an initial state (bulk filament) to an arrangement of nine extruded filaments in order to determine the neighboring effects on Young's modulus, highlighting the influence of the contact area between filaments on the mechanical behavior of the part.

A second model considering a filament with an elliptical cross section, closer to the real geometry of the deposited filaments, was designed. In this case, the length of the major axis of the ellipse was the raster width (0.3048 mm) and the minor axis of the ellipse was the layer thickness employed to make the part (0.1778 mm) (see Figure 3b), the length of the cylinder was 0.609 mm.

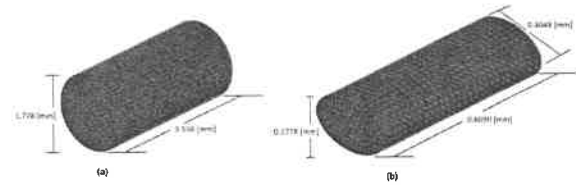


FIGURE 3. a) Isolated circular filament model, b) isolated elliptical filament model

Then, a third model with an arrangement of nine filaments with an elliptical cross-section was designed. Filaments were not bonding with each other, i.e., only their external surfaces were in contact with each other (see Figure 4).

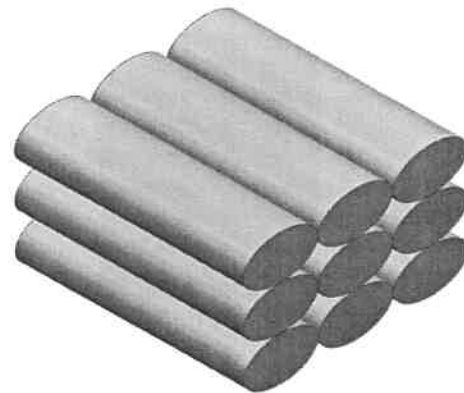


FIGURE 4. Filament arrangement without bonding.

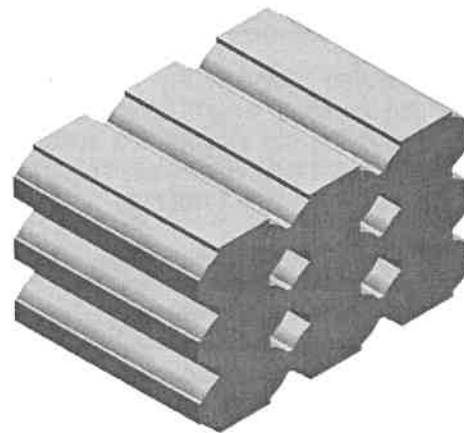


FIGURE 5. Filament arrangement with bonding.

A straight bonding contact between inter-layer and intra-layer filament were considered. A meso-structure was developed for the study. The model depicts the meso-structure when a FDM process deposits rasters with raster angle equal to 0°; in it, all the inter-layer filaments were parallel to each other. In the model, bonding

contact along the filaments is considered continuous (see Figure 5).

Four important parameters were considered to develop the CAD models: CL (contact length between layers) is the inter-layer bonding length, CF (contact length between filaments) is the intra-layer bonding length, RW (raster width), and LT (layer thickness) depends on the tip size (see Figure 6).

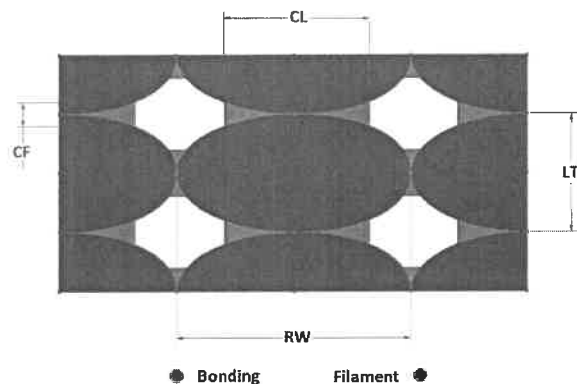


FIGURE 6. Filament arrangement CAD parameters

RESULTS

Table 5 shows the manufacturing parameter setup used to perform the FEM analysis.

TABLE 5 CAD model parameters

RW	0.3048[mm] (Nominal);
LT	T12 (0.1778 [mm])
CF	0.06 [mm] (Nominal); 0.04 [mm] (Proposed); 0.08 [mm] (Proposed)
CL	0.17 [mm] (Nominal); 0.1 [mm] (Proposed); 0.2 [mm] (Proposed)

A bonding ratio (BR) was calculated using the next relation:

$$BR = CL/CF \quad (1)$$

Table 6 shows the variation of the bonding ratio:

TABLE 6. Bonding ratios

BR	CL [mm]	CF [mm]
2.83 (nominal)	0.17	0.06
1.67	0.1	0.06
2.12	0.17	0.08
4.25	0.17	0.04
3.3	0.2	0.06

To obtain the Young's modulus of the different filaments, traction of 30 MPa was applied axially to one of the ends of the filament, whereas the opposite end was constrained.

Figure 7 shows the variation of the geometry of the filament and its influence on Young's modulus.

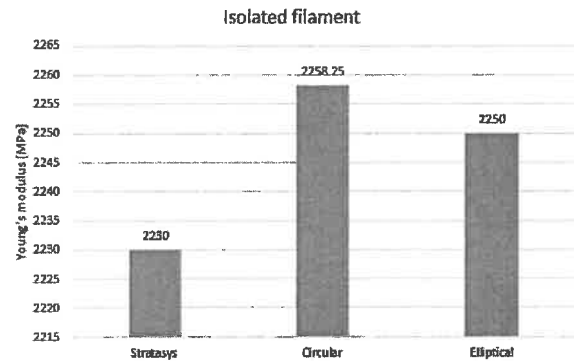


FIGURE 7. Young's modulus of the isolated filaments.

The Young's modulus of the Stratasys model was obtained from the datasheet of the ABS-M30 [7]. The circular section filament was considered as the filament before the extrusion process and analyzed by FEM, the elliptical section filament had a major axis length equal to 0.3048 mm (raster width) and a minor axis length equal to 0.1778 mm (layer thickness).

Figure 8 shows the influence of the bonding ratio on the Young's modulus and the comparison with the isolated filaments; no bonding corresponds to the arrangement of filaments with no bonding. In this case, raster width and layer thickness, for all the filaments, were 0.3048 mm and 0.1778 mm; the Young's modulus of the nominal bonding ratio corresponds to the arrangement of filaments with CL and CF obtained by X-ray CT images; the next BR corresponded to the values displayed in Table 6. Figure 9 shows the influence of the CL on the Young's modulus of the part. In this case, the CF was fixed in the nominal value and both a decrease of 0.2 mm as well as an increase of 0.1 mm of the nominal CL (0.17 mm) were included.

Figure 10 shows the influence of the CF on the Young's modulus of the part. In this case, the CL was fixed in the nominal value, and both a decrease of 0.08 mm and an increase of 0.04 mm of the nominal CL (0.06 mm) were proposed.

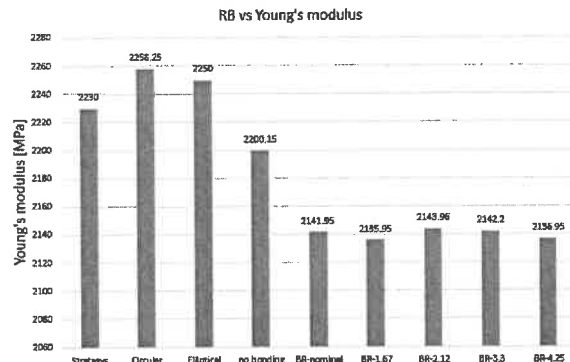


FIGURE 8. Isolated and arrangement's Young's modulus

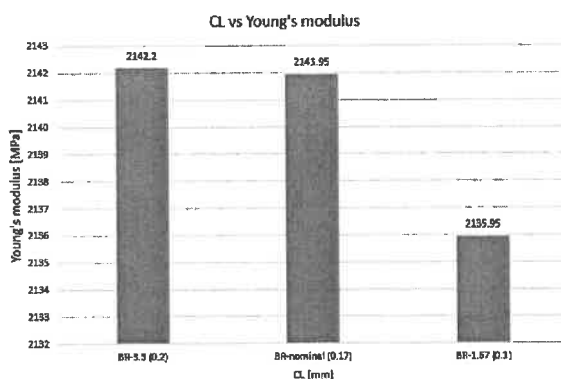


FIGURE 9. Influence of the CL on the Young's modulus

Figure 10 shows the influence of the CF on the Young's modulus of the part. In this case, the CL was fixed in the nominal value, and both a decrease of 0.08 mm and an increase of 0.04 mm of the nominal CL (0.06 mm) were proposed.

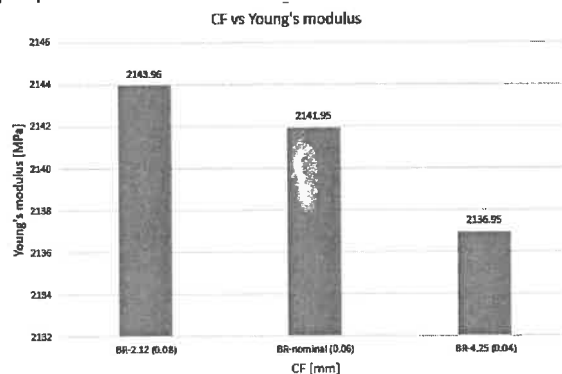


FIGURE 10. Influence of the CF on the Young's modulus

Results

The results show the decrease of the Young's modulus from the isolated filament for an

arrangement of filaments; it should be noted that the value obtained by the FEM analysis is bigger than the nominal value reported by Stratasys. This difference depends on the finite element method chosen for the analysis; however, comparing the Young's modulus between filaments after and before the extrusion, and considering that the material properties for both FE models are the same, it is possible to observe that the geometry of the filaments affects the value of the Young's modulus.

The results of the three arrangements show a decrease of the Young's modulus. The comparison between the arrangement with no bonding and the BR-nominal one shows that, although the section geometry has a smaller area than the last one, the influence of the bonding length on the Young's modulus is important because the Young's modulus is reduced in 2.7 percent. The results show that small variations of CF or CL in the arrangement leads to a small variation in the Young's modulus; this can be observed in both the decrease and the increase of the bonding length. However, although the results show a relation between bonding length and the Young's modulus, more experimentation on the variation of this bonding is necessary.

In addition, it is not possible to guarantee that by increasing the BR, the Young's modulus of the part will increase since this value depends on which length is increased, CL or CF. Results of BR-2.12 and BR-3.3 show that both ratios increase the Young's modulus regarding the nominal BR; nevertheless, it is important to stress that BR-2.12 is less than nominal BR and BR-3.3 is bigger than nominal BR. This results show that by increasing CF, the Young's modulus can be further increased than the value of the CL, but this cannot be generalized.

CONCLUSIONS

The bonding length between filaments is a crucial factor to be considered to predict the mechanical properties of parts made by the FDM process. A suitable determination of the geometry and length is necessary to develop a reliable computational model. Results show that the Young's modulus varies depending on the bonding ratio; nonetheless, these results cannot be generalized.

The analysis of the sample by X-ray CT images gives relevant information about the contact

length between filaments, which allows generating models that can predict the mechanical properties of the FDM parts. However, it should be taken into account that the CT images show that this bonding length is not constant along the filaments and that there are zones where no contact exists. In addition, it is necessary to carry out a correct identification of the geometry of the neck that allows improving the FE model to obtain reliable results about the Young's modulus. More BR values should be considered to be applied in the FE analysis to study the influence of the BR on the Young's modulus. Even though it is possible to make FE simulations of the bonding length between filaments. It is necessary to study how this defect can be modified in the manufacturing parameter setup in order for these simulations to have an impact on the design and manufacturing parts by the FDM process.

It is important to take into consideration that the results shown in this work cannot be generalized because they are related to a particular case of study and more experimentation on how parameters such as the angle raster in correlation with the bonding length between filaments affects the Young's modulus of FDM parts.

ACKNOWLEDGMENT

This work has been financed by DGAPAUNAM through the grant PE-104014. Financial support from CONACYT LN-232719, LN-272897 and INFR-205502 is also acknowledged

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INFORMATION-RICH APPROACH TO NON-DESTRUCTIVE NON-CONTACT MEASUREMENT PLANNING, INSPECTION AND VERIFICATION FOR ADDITIVE MANUFACTURING

Petros Stavroulakis¹, Patrick Bointon¹, Nicholas Southon¹, Richard Leach¹

¹Manufacturing Metrology Team

University of Nottingham, Nottingham NG7 2RD, UK

INTRODUCTION

The recent proliferation of non-contact optical 3D instruments in manufacturing is the most reliable indicator for the constant need of the manufacturing industry to inspect the form of their products quickly and efficiently, and with the necessary detail to allow quality control. The reasons for this need can vary from optimising production-line control to final product quality inspection and functional evaluation.

The fulfilment of the potential advancements in speed and resolution promised by the most popular non-destructive non-contact optical methods (i.e. structured light projection and laser triangulation [1], [2]) compared to existing contact form measurement techniques are typically impeded by the business practice of the generalisation of commercially available metrology equipment to appeal to as large a customer base as possible, at the lowest possible cost. This business model, as sound as it is for selling as many metrology products as possible, does little to push the limits of the current technologies to satisfy the needs of the most demanding customers (e.g. aerospace, automotive and medical) which usually require their measurement systems to work at the limits of what is physically achievable in the most efficient manner possible, and tailored to their specific needs. Hence, most large manufacturing organisations resort to in-house development or commissioning of custom solutions for their measurement needs.

The rise of additive manufacturing (AM) has levelled the playing field and now much smaller organisations have the ability to produce the same, if not higher complexity, products compared to traditional manufacturing organisations, even if they do so at much lower throughputs. To add to this, AM organisations can make different products in every manufacturing run, so a custom measurement solution may not be of use, as it would be too inflexible to deal with all the possible products their AM machines could

produce. Thus, what AM organisations lack is the ability to provide themselves with tailored custom solutions, such as those available to larger industries, to satisfy their measurement requirements and ensure the products they produce for a demanding customer are to specification, in tolerance and fit for purpose.

This gap between what is physically possible and what is commercially available could benefit from an intermediate genre of form measurement products and strategies which are flexible enough to be adaptable to a wide range of products but still possess the high specifications and quality of custom solutions.

The Manufacturing Metrology Team at the University of Nottingham is addressing the above issues with a mix of different metrology strategies to make form measurement faster, more accurate and more efficient for use in AM. The theme which we will use to accomplish this is “information-rich metrology” (IRM). IRM is the combination of accurate modelling of the interaction with the object being measured (i.e. the interaction of light with the surface in the case of structured light systems) with all the *a priori* information that is available (see Figure 1). Often when we manufacture something, and especially when we use AM, we have a large amount of information about the object being manufactured, e.g. the CAD data gives us the nominal form and we have usually characterised the surface texture to a high degree of confidence. In many cases, the *a priori* information allows us to solve the complex mathematical problems we encounter when trying to model the interaction with the object being measured (the inverse problems). Our research is focusing on accurate mathematical modelling to allow us to optimise a given measurement scenario. IRM can allow us to minimise the measurement time (e.g. by optimising the number of views we need to take to capture the form information) and increase the spatial bandwidth in which we measure (for example, by allowing us to

measure high slope angles using multiple reflections). Our ultimate goal is to have a form measurement system, based entirely on camera technology that allows us to get the maximum amount of form information with the minimum effort. This will need advances in the optical technology, in the mathematics required for modelling the inverse solutions and in smart measurement planning systems.

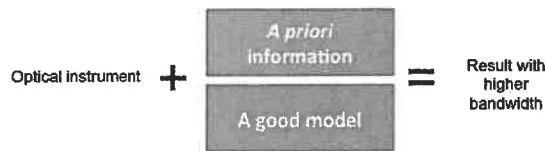


FIGURE 1. The "information-rich metrology" philosophy

SYSTEM DESCRIPTION

The planned system for AM applications would be a constellation of multiple cameras and projectors where *a priori* information is used to optimise the measurement result in the minimum amount of time. The flowchart of the procedure is shown in Figure 2 and the steps are described below:

- Initially, the CAD model of the object has to be translated from its input file format to either triangle-based or polygon format and loaded in a tabular form that is recognised by the control software. Only open file formats will be used initially to reduce file translation inaccuracies and proprietary information obstacles. A quantitative understanding of the uncertainties introduced at this stage will be essential.
- Following the import of the CAD data, the necessary simulations of the measurement process will take place using the aforementioned mathematical model of the object and the measurement setup. One example of the simulations which will be run to optimise the measurement process is shadow prediction [3], where the shadows cast from each projector around the object are calculated and, therefore, accounted for. This simulation step will allow a suitable measurement strategy to be planned.
- After the measurement strategy has been selected, a minimisation exercise will take place to ensure that the measurement is taken with a single attempt and as fast as possible.
- The system will auto-configure itself to the setup calculated in step 3 and the measurement will be taken.
- After the measurement is taken, a final comparison with the CAD model will be used as feedback to determine whether the set of expected points have been calculated successfully and with the required fidelity.
- Finally, if an error in measurement is acknowledged, or if a more detailed measurement is required for specific parts of the object, a re-try will be attempted for a specific area or group of areas with different parameters or with a more accurate measurement technique to improve the result. Only one re-try per measurement area will be allowed.

SUMMARY

IRM has a lot to offer in terms of assisting metrology systems to achieve their full potential in an efficient and timely manner. IRM is especially useful for AM applications where *a priori* data for the measured object is readily available. When object data is combined with a model of the measurement instrument, simulations of the measurement process can be used to overcome problems more deterministically than would be possible in an open-loop measurement scenario that ignores the *a priori* data.

A framework for an optical form measurement system for AM applications that is based on the availability of CAD data and optical models of the measurement system is presented. Shadow prediction (a fundamental problem in structured light systems) can be dealt with effectively with prior knowledge of the light source, camera and the measured object. Efforts are currently focused on attempting to realise the concepts presented here in a manner which would be accurate but also practical enough to realise in an industrial AM measurement scenario.

ACKNOWLEDGEMENTS

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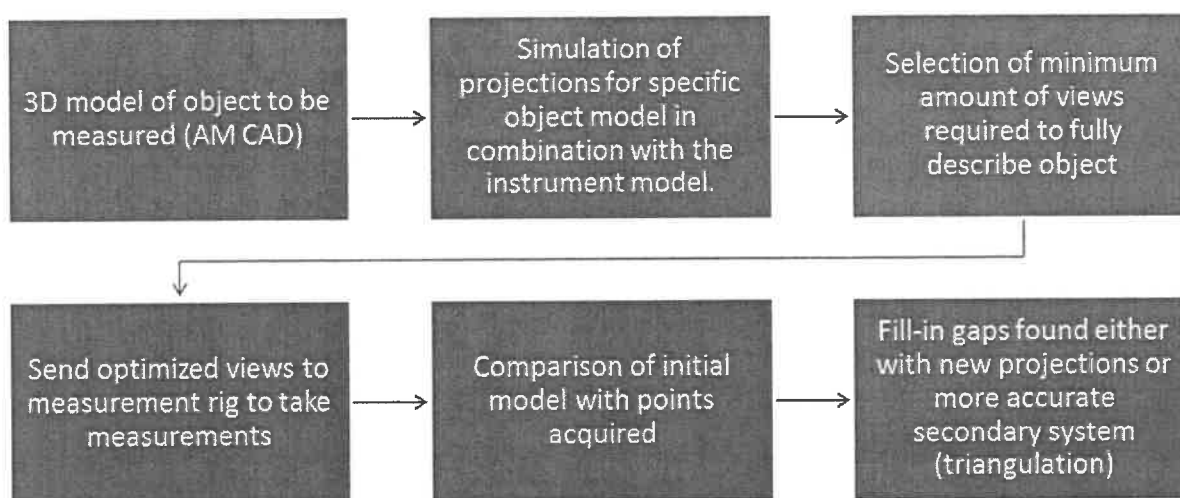


FIGURE 2. A flowchart of the measurement procedure envisaged for the AM form measurement system using IRM.

ENTRY POINTS FOR METAL ADDITIVE MANUFACTURING IN PRECISION EQUIPMENT

Ton Peijnenburg¹, Cas Wijnstok¹, Gerrit Oosterhuis¹, and Martijn Vanloffelt²

¹Technology and Development group

VDL Enabling Technologies Group

Eindhoven, The Netherlands

²3D Systems Leuven

Leuven, Belgium

INTRODUCTION

While the use of metal additive manufacturing (AM) is gaining traction in precision equipment manufacturing, VDL Enabling Technologies Group together with their customers and 3D Systems Leuven (formerly Layerwise) continue to evaluate application areas for manufacturing technology readiness and functional benefits.

Originally a technology for rapid prototyping, metal AM is now rapidly evolving into a mature manufacturing technology with unique capabilities for distinct features such as internal channels for cooling water or gas delivery, or multiple degree-of-freedom flexure mechanisms.

This paper gives an update on the continuing evaluation, with specific updates on cleaning and flexure mechanisms. It builds on previous papers [1], [2], [4].

IMPROVING FUNCTIONAL PERFORMANCE

The following test case groups have been defined by VDL ETG, based on functional performance areas typical for precision mechanical and precision mechatronic systems, and inspired by examples from their precision engineering practice:

- Heat and flow
- Integrated mechanisms
- Structural dynamics
- Odd materials

The groups of heat and flow and integrated mechanisms will be described in more detail.

Heat and flow

Particularly in the group of heat & flow we have worked on several suitable test cases that have yielded useful results. Applications are:

- thermal control structures aimed at creating a uniform temperature for a technical

substrate, with K/m as performance indicator [3];

- thermal control structures aimed at removal of heat, e.g. from an electromagnetic actuator, with K/W as performance indicator;
- liquid and gas delivery manifold structures, where channels should be smooth and clean.

The feature of interest in this group is the (internal) channel for gases or fluids; this feature can be realized with a high degree of complexity relative to machined channels that are now most widely used, while there is no penalty in terms of having to close the machined channels.

The cleaning of these internal channels provides challenges that have not yet been resolved to a satisfactory level for all of our test applications. Our findings will be discussed briefly in the next chapter, to give an idea about the status of the development.

Integrated mechanisms

Mechanisms for precision motion are often based on flexures to guarantee motion which is free of friction and backlash. Combining degrees of freedom (DOF) is achieved by assembly of multiple parts that offer one or two degrees of freedom. The combination of several degrees of freedom in these parts is limited due to traditional manufacturing technologies; typically, Electric Discharge Machining (EDM) is used for such parts.

Metal AM allows to further integrate mechanisms, allowing all required degrees of freedom to be in a single monolithic part, eliminating interface- and reference features and thus reducing cost. After having looked at dynamic flexure mechanisms, we have now also explored (quasi-)static mechanisms that are used for alignment of optical elements.

Several flexure mechanisms for single optical elements, such as mirrors or corner cubes, have been designed and realized. Most of these have been manually designed, integrating more degrees of freedom in a single part than is possible with constraints from the traditional manufacturing technologies.

In addition, levers and other control structures can be integrated into the same single part. To demonstrate these advantages, a module has been designed and built for aligning a laser beam to an optical beam path, see *FIGURE 1*.

The module allows two mirrors to be adjusted in a synchronized manner, offering separate adjustment for angular and linear DOF of the laser beam. The synchronized adjustment allows for direct, intuitive adjustment without iterations, saving on adjustment time in production or during service. An additional benefit in this respect can be created by locating the adjustment controls such that they are well-accessible, further reducing service time.

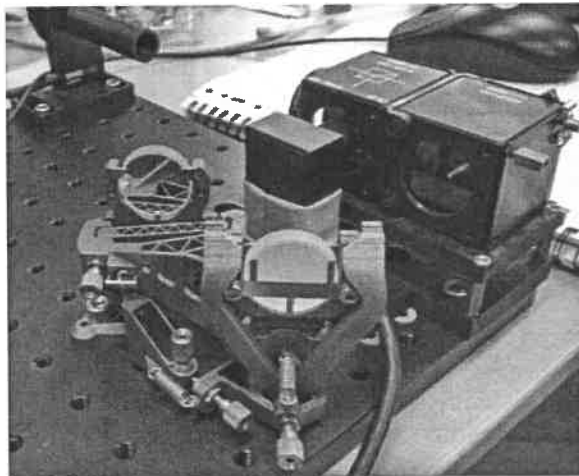


FIGURE 1. Integrated adjustment mechanism offering synchronized adjustment of two mirrors

As stated before, several benefits are realized by means of a single part design that can be economically manufactured using AM:

- offer all required degrees of freedom for the optical elements;
- synchronously actuate the desired degrees of freedom to decouple adjustments;
- provide controls at an accessible location;
- limit post-machining only to the interfaces for optical parts;

- prevent accurate features required only to assemble a module from multiple parts ("self-inflicted collateral accuracy").

PARTICLE CLEANLINESS

The goal we set ourselves is to realize metal AM parts for gas delivery systems according to semiconductor equipment cleanliness requirements. This section will briefly discuss the measurement setup, test part design, cleaning processes and the results.

Measurement setup

Particle measurements are done in line with specifications from one of our semiconductor equipment customers and performed both at VDL ETG as well as Philips Innovation Services for comparison purposes, see *FIGURE 2*. Outgassing (TOC) is measured at Philips Innovation Services only.

Particle cleanliness is specified to be below ISO 14644-1 class 2. Molecular cleanliness (outgassing) is specified in line with requirements for UHV systems, e.g. with charged particles.

Air born particle measurement set up @ VDL ETG

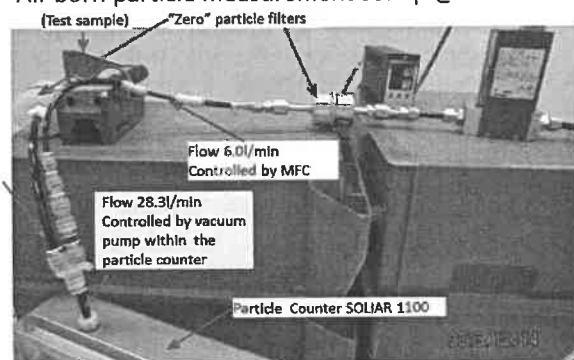


FIGURE 2. Particle measurement setup.

Test part design

The requirements for the test part were set as follows.

- Comparable to parts for gas delivery
- Manufacture with metal AM process
- Channel with inner diameter of 2 mm
- Channel with minimal length of 400mm
- Can do particle- and TOC measurements
- In aluminum, stainless steel and titanium

For the resulting test part, see *FIGURE 3*.

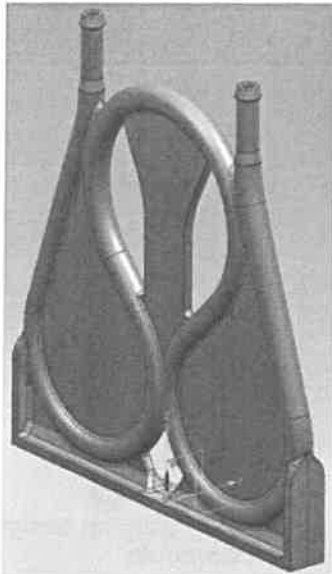


FIGURE 3. Test part for cleanliness experiments

Cleaning processes

An initial selection of cleaning procedures was done using a selection matrix method, comparing suitability of specific cleaning techniques to features of the parts and cleanliness requirements. Alkaline, acid (pickling), ultra- or megasonic and brushing were preselected. In addition, our partner 3D Systems Leuven offers SILC cleaning for their titanium parts; the specifics of this cleaning process are trade secret.

Cleanliness results

A DOE series was executed with 3 materials and 3 cleaning methods. The results for the particle cleanliness are shown in the diagram, see **FIGURE 4**.

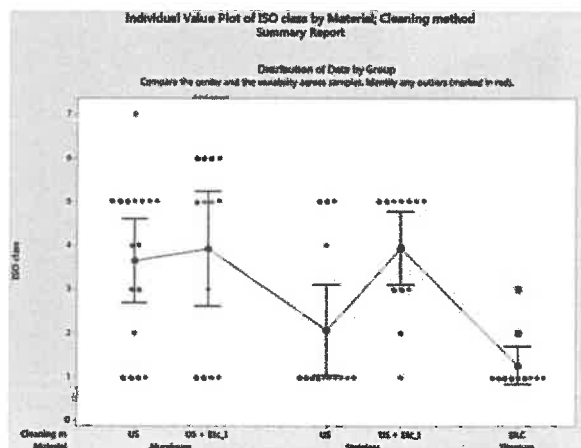


FIGURE 4. Results of particle cleanliness for different materials and cleaning techniques

Titanium in combination with SILC is compliant with our particle specification. Stainless steel and aluminum cleaned with ultrasonic are also compliant, aluminum however only after extensive flushing – four days of continuous testing. Etching did not seem to improve particle cleanliness in this series of experiments. We are conducting more experiments to assess the effectiveness of etching, since experience from our partner indicates there should be a benefit.

Outgassing is not discussed in detail in this paper. It was found to be compliant to our specification for all test parts and all materials.

DESIGN OF AN OPTOMECHANICAL MECHANISM

A laser alignment module has been selected as a test case for an opto-mechanical “monolithic” assembly using metal AM. The part will contain multiple integrated elastic hinges and levers.

The laser alignment functionality is currently mostly implemented as two tip-tilt mirrors, or one window and a mirror. It aligns (angular) and adjusts (position) the laser beam to the optical path of the rest of the system to which it is coupled, and will need readjustment when a new laser is installed.

The requirements for the functionality are as follows:

- Converging adjustment, meaning a subsequent adjustment does not or minimally influences previous adjustments;
- Free of friction: friction will lead to hysteresis. This in turn will make the effect of an adjustment unpredictable;
- Free of play: play will cause difficulty during adjustments and finally has to be removed to lock the position of the optical element.

All these requirements can be fulfilled with conventional manufacturing techniques in combination with traditional mechanical design. However, the use of metal AM can give an additional benefit over conventional manufacturing methods. AM typically results in a monolithic part, which is by definition free of friction and play. Parts and/or functions can be integrated in the monolithic part, minimizing assembly and interfaces between parts and resulting in a more compact structure.

Please note that a converging adjustment is the result of the design; the manufacturing method has no influence on this.

Detailed requirements

Based on a postulated laser beam uncertainty (including the laser mount) of ± 1 mm and ± 1 mrad, as well as a general idea on the layout of the optical system that follows, the requirements for the alignment unit are formulated as follows.

- Angular adjustment range ± 7 mrad
- Angular resolution $0.4 \mu\text{rad}$
- Linear adjustment range ± 2 mm
- Linear resolution 0.01 mm
- No transmissive optics to be used – the system should be suitable for short wavelength lasers as well

Design

As a first step in the design process, the required adjustment inputs for the various adjustment ranges were calculated. For the angular adjustments, very small inputs were required in the order of $20 \mu\text{m}$. For these adjustments, levers were introduced so that more simple adjustment screws can be used instead of more expensive, direct input differential screws.

Starting from the two mirrors, the mechanisms were designed, taking into account the constraints as provided by 3D Systems Leuven, see *FIGURE 5*. Ti6Al4V has been selected as material, because of its higher allowable stress than 316L, and better surface quality. Flexures are considered static with 4 adjustments per year. Stress levels in the flexing areas are kept 25% below the yield stress. Roughness is subtracted from flexure thickness for calculation.

Source: 3DS/Layerwise	316L	Ti6Al4V
Minimum wall thickness vertical	0,3 - 0,4mm	0,3 mm
Minimum wall thickness horizontal	0,6 - 0,7mm	0,5 mm (near overhang angle)
Minimum angle of overhang	55°	45°

FIGURE 5. Design constraints

The design was then further optimized for 3D printing based on a design review with the supplier. Shapes were then made smooth and rounded, see *FIGURE 6*. The total weight of the mechanism could be kept as low as 200 g.

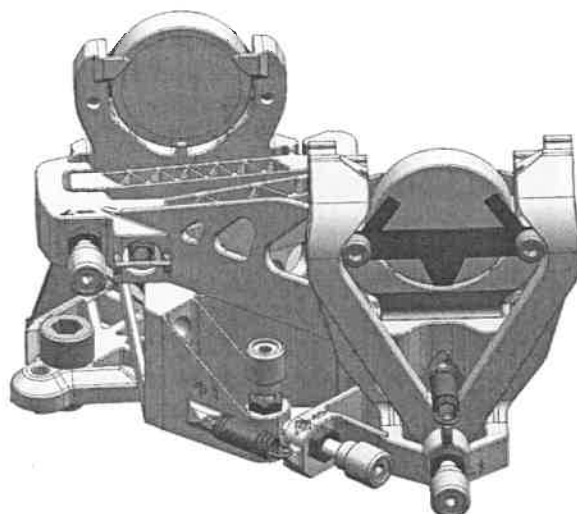


FIGURE 6. Isometric view of resulting design for two-mirror adjustment module

Manufacturing

The part is printed at 3D Systems Leuven, and delivered to VDL ETG on its print base plate. The base is used for clamping the part during cutting of the mirror mounts and cutting of the threaded holes for the adjustment screws, see *FIGURE 7*.

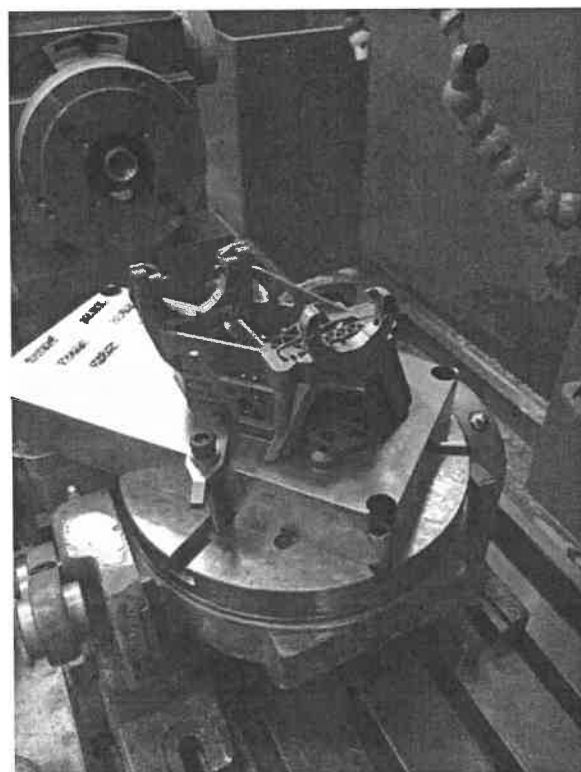


FIGURE 7. Ready for post-machining still attached to build base plate

Wire EDM is then used to clear the flexures, and separate the part from the build base, see *FIGURE 8*.

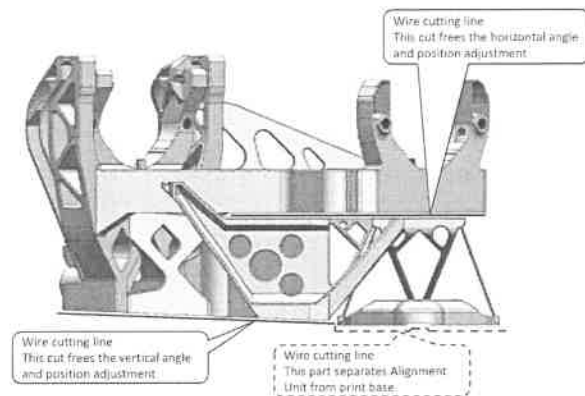


FIGURE 8. Side view showing wire cutting locations to a) free flexure elements and b) free the assembly from the base

Validation

The two-mirror adjustment module has been integrated into a test set-up, whereby a laser and two Position Sensitive Device (PSD) sensors are added to create a functional environment, see *FIGURE 9*. The alignment ranges are according to design and the cross-talk between the angular and position alignments is less than 1%.

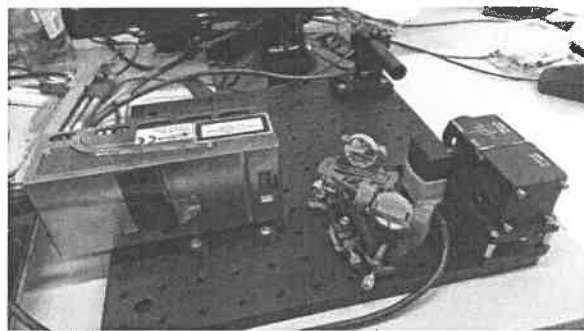


FIGURE 9. Demonstrator with laser and two PSD sensors for validating the two-mirror module

Topology optimization

Together with Delft University, a start has been made with applying topology optimization to the multiple-DOF flexure mechanisms. Preliminary results are available [5]. A case has been explored for a tip-tilt mirror mount with prescribed controller locations, see *FIGURE 10*.

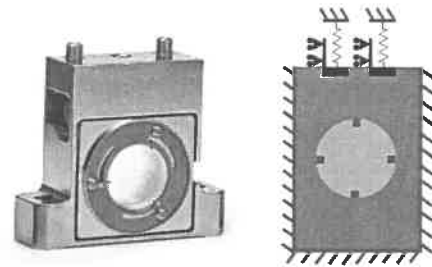


FIGURE 10. Mechanism for mirror tip-tilt a) existing design, b) schematically and c) from topology optimizer

Starting with an empty design volume in combination with explicit boundary conditions, e.g. for mirror movement and controls location, poses significant requirements on the algorithms and compute infrastructure. A proposal is now formulated to both use traditional kinematic design techniques to generate initial configurations for the mechanism that is to be designed, and to use this initial configuration as input for the optimization process. It is expected that such a hybrid approach will improve the outcome of the topology optimization process and make it suitable for manufacturing.

Further research on this topic has been defined by the group of Van Keulen from Delft University of Technology, together with industrial partners including VDL ETG, and is currently awaiting funding allocation.

CONCLUSION

In addition to the heat & flow application area, also the area of (quasi-) static flexure mechanisms for adjustment of optical components holds promise for the capabilities offered by metal AM. It offers functional benefits that may accelerate the introduction of AM into the field of precision equipment. Currently, we have to rely on traditional design techniques, until automated optimization techniques have further matured.

A test case has been explored for a two-mirror module for laser alignment. A monolithical part has been designed and realized to hold two mirrors and allow for decoupled alignment of linear and angular DOF of a laser beam. The module has been integrated into a test set-up to confirm cross-talk between decoupled DOF to be less than 1%.

Cleaning of internal channels in metal AM parts for gas delivery functionality has been investigated. A test part has been designed and manufactured in different materials. Particle cleanliness is good for titanium and stainless steel, and for aluminum only after extensive purging. Molecular cleanliness (outgassing) is sufficient for all materials.

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DIMENSIONAL ACCURACY OF PRINTED END EFFECTOR

Cas Wijnstok¹, Gerrit Oosterhuis¹, Martijn Vanloffelt² and Steve Fournier³

¹ VDL ETG Technologies & Development
Eindhoven, The Netherlands

² 3D Systems
Leuven, Belgium

³ KLA-Tencor,
Milpitas CA, USA

INTRODUCTION

A vacuum operated end effector for handling wafers has two 'fingers' with a vacuum distribution channel and three wafer contact points (See FIGURE 1 and FIGURE 2). At the wafer contact points, pads of a specific polymer are adhesive-bonded to the metal part. The vacuum channel is conventionally manufactured as a groove with a lid bonded on top of it using adhesive. This adhesive bonding process has been susceptible to yield loss and reliability issues. Additive manufacturing (AM) was one of the options to improve the performance on these aspects.

The part is suitable to manufacture using additive manufacturing as it has internal channels and requires large amounts of material removal with conventional manufacturing. Also, weight and resonance frequency influence the robot throughput performance, which typically improve when (re)designing for AM.



FIGURE 1. Original design of end effector. Wafer contact points are shown in yellow.

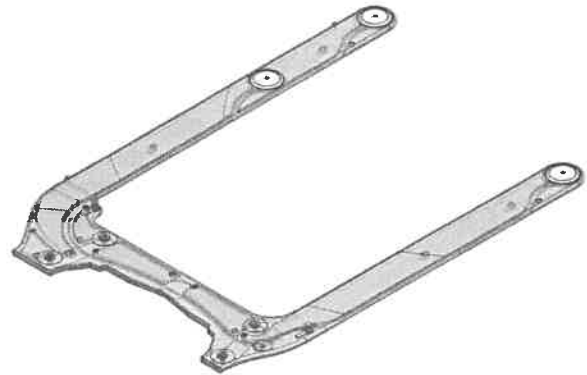


FIGURE 2. Final design of end effector suitable for additive manufacturing. Printed body is displayed transparent grey, wafer contact pads are shown in yellow, these are glued on after post-machining.

During the redesign for AM, all the typical challenges in designing for additive manufacturing had to be overcome: applying the correct overhang angles, removing powder from cavities, incorporating features for post-machining and minimizing cross sectional areas per build layer.

Although all design rules for AM had been followed and the part proved to print successfully straight out of the first build iteration, the printed end effector had an unexpected defect: the 'fingers' pointed inwards by 1.5 mm. The following will elaborate on design, manufacturing results, test builds and the solution for the defect.

DESIGN FOR AM

The existing design of the end-effector had to be modified to make it manufacturable using Selective Laser Melting – SLM a.k.a. Laser Beam Melting - LBM, which is the technology of choice for the given object size and level of detail.

Requirements

The design boundary condition was to make a full form-fit-function redesign requiring all the interfaces as well as the functional response to be exactly maintained.

In the existing design, the end-effector was milled from a flat plate, with a groove for the vacuum channel, which is sealed by a thin plate and adhesive as given in FIGURE 3 – upper figure.

Apart from the interfaces, the functional performance aspects influenced by the geometry of the end-effector are the ability to clamp a wafer and the time needed to do so. The first is mainly influenced by the flatness of the pads with respect to the reference plane at the robot wrist. The latter is mainly driven by the volume of the vacuum channel. Also, the outer dimensions of the end-effector should fit within the given tolerance budget for the robot positioning. The most important other geometrical requirements are:

- Minimal clearance from wafer to base: 0.4 mm
- Finger spacing tolerance: 0.2 mm
- Flatness between pads: 0.13 mm
- Deflection under loading (wafer): 0.26 mm

To achieve the same clamping time, the vacuum channel should have a volume and flow resistance that closely resemble the original milled design. The dynamics of clamping a wafer also relate to the vacuum flow resistance. Given the rough walls that are typical for the SLM process, this could have an impact. However, at the current channel dimensions and the flow regime at which it operates, this effect can be neglected as confirmed later by a clamping test performed on the finished printed End Effector.

Further, the end-effector should not generate any particles, which for this case is specified by the ISO clean air class that results when very clean air (ISO class 1) is forced through the vacuum channel. In addition, the end-effector should be cleanable with cleanroom cloth, which translates into a roughness requirement for the outside surface area, which in the original requirement is $Ra = 16\mu m$.

Design approach

To be able to apply the typical design rules for SLM [1], the starting point was using just the

existing critical interfaces to the polymer pads, the vacuum connection interface and the robot wrist and set-up the complete design anew within the available volume as a boundary condition.

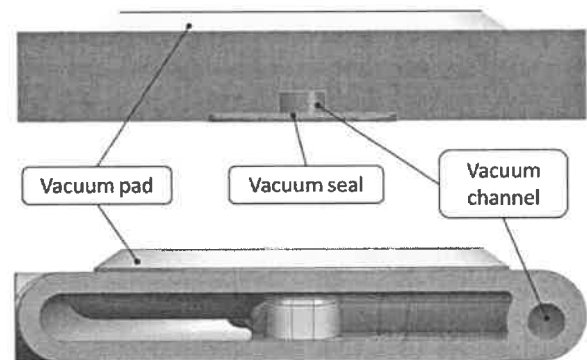


FIGURE 3. Cross section of one finger of the end-effectors. Upper shows the original design, lower shows the printed version.

The first step is typically to determine the build orientation, which in this case was chosen to be upright with the fingers pointing upwards (FIGURE 4). This choice minimized the cross sectional area per build layer, thus reducing residual stresses that may lead to unflatness or other dimensional distortions.

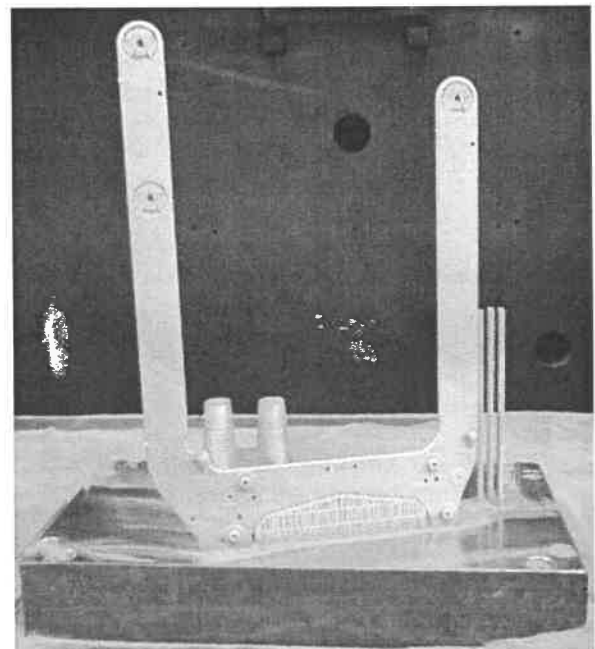


FIGURE 4. Unfinished printed end effector still attached to DMLS base

Further, the design was set up using minimal material, hence a hollow shell in this case. Interior volumes were left empty and reinforcements were designed at the locations where the part needs to be clamped for post-machining. Minimizing mass serves two main purposes: 1) lowering the cost of printing, and 2) tuning the resonance frequency.

Another important design rule is to minimize the area to be post-machined. SLM typically yields accuracies in the range of ± 0.1 - 0.2 mm. Hence, post-machining is required on all critical interfaces. Therefore, a design target is to minimize the critical surface area. This was achieved by designing the outer shell to be slightly below the robot interface reference plane, such that only the interface areas needed to be machined to meet the flatness and lateral tolerances. All features to post-machine were given a machining allowance that accounts for the ± 0.2 mm printing uncertainty. In other words we thickened the critical areas so we can machine off the excess to meet specifications.

Finally, the vacuum channel was designed in as well as the fillets, curves and support structures

needed to avoid overhang angles, as well as the right wall thickness to ensure leak tight channels after post-processing.

Design result

The design result is shown in FIGURE 5, where the most important design-for-AM features are indicated. As a result of minimizing the material, the weight of the part has been reduced by 41 %.

The design has been verified by Finite Element Analysis (FEA) to check the stiffness i.e. deflection with and without a load (wafer) as well as the resonance frequency. These are important parameters that determine the position accuracy and speed of operation of the wafer handling robot.

The FEA showed that the deflection and first resonance frequency while carrying a wafer are identical to the original design. The printed end effector shows an increase of 20% in resonance frequency for the unloaded situation. The unloaded deflection is approximately halved to 0.07mm.

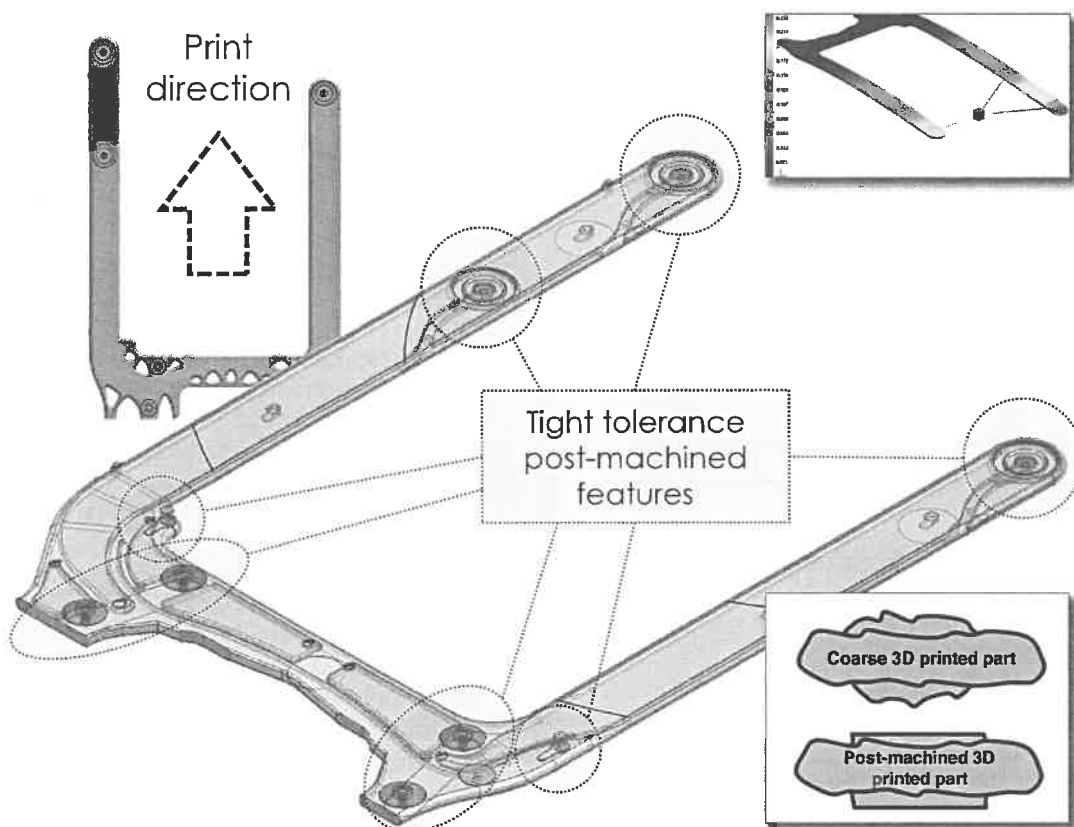


FIGURE 5. Overview of the main designed features for AM

MANUFACTURING RESULTS

Printability

As a result of the AM-optimized design that respects the typical SLM-design rules, the additive manufacturing process was successful from the first run. Apart from the geometric tolerances (see next paragraph) the part fulfilled the expectations after the additive manufacturing process.

Cleanliness

After printing, the end-effector exterior has been cleaned using normal semiconductor cleaning processes. The channels have been cleaned using ultrasonic assisted flushing of subsequently a detergent, tap water and demi water. Cleaning is finished by flushing clean dry air followed by vacuum drying.

On two builds, particles counts have been measured, the results of which are presented in TABLE 1. These results are promising and correspond to an ISO cleanliness class 3. In addition, a cleaning process for stainless steel channels is under development at VDL and 3DSysystems frm. Layerwise, as is reported in [2]. These show that achieving ISO1-ISO2 class air can be achieved when using AM gas supply tubing.

TABLE 1: Results of particle measurements on both end effectors.

Average Particle count per vacuum port (#/m3)		
Particle size	Build #2	Build #3
<0.1 um	424	?
<0.2 um	141	150
<0.3 um	71	50
<0.5 um	35	6
<1.0 um	35	9
ISO class	ISO 3	ISO 3

Geometric tolerances

Post-machining was straightforward and did not yield any surprises.

Dimensional measurements were done:

- directly after printing
(except for the first build - Part 0)
- after stress-relieve heat treatment, build-plate removal using wire -EDM (electric discharge machining) and shot-peening
- after machining
- after assembly of the pads,

After build plate removal, the first build of the end effector showed acceptable results for flatness. However the two legs were pointing inwards by 1,5mm at the end of the fork tips, which was far outside the post-machining allowances, making it unfit for use.

This effect was completely unexpected due to the small overall layer cross-sections, which directly correlate to the amount of thermal stress that is created during the SLM-process, across the build height. Therefore, no special arrangements were taken in the design to avoid it. The main focus was to achieve the flatness.

Dimensional deviations on this scale were not expected directly from the printing process while the cross sections of both fingers are identical. Meaning that if they would deform, it should be similar for both fingers. Therefore, the cause of this defect was expected in the post-processing of the part. Not knowing exactly what caused the deviation, the deformation was taken as a given and the design was compensated to anticipate the observed dimensional deviation in part 0. Two approaches were used:

1. Implementation of additional supports between base plate and the End Effector. This introduces higher stiffness and heat sinking capabilities during the build process.
2. Pre-compensation of the model initially by implementing an opposite bend/skewness in the 3D printing file with a magnitude similar to the deformation measured on part 0.

For the corrected build, the spacing between the legs was checked directly after printing and was within 0,2mm from nominal compared to the two different 3D models printed. After post processing the legs were pointing outwards by 2mm for both test cases. All the different states are illustrated in FIGURE 6.

INTERPRETING THE RESULTS & SOLUTION

The difference between the first build (Part 0) and Part 1 and 2 was the heat treatment applied which ultimately was found to be the root cause of the effect we observed. Instead of a stress-relieve in the initial build (Part 0), an annealing cycle was applied in Part 1 & 2. The main difference is that the cooling rate of an annealing

cycle is much higher than of a stress relieve cycle.

In general SLM parts the type of heat treatment does not affect the geometric tolerances. However, the thin geometry of the part combined with the thick substrate plate causes non-uniform cooling during the high cooling rates applied. This consequently creates stresses in the part, which may differ from the stresses created in the SLM-process, which in this case yielded opposite deformations in Part 1 & 2 compared to Part 0.

A third build with test case 3 & 4 was performed, using the same design modifications as case 1 & 2 but this time, using a heat treatment for stress relieve identical to the initial build. The end result was a product with deviations that were within the available post-machining allowance (part 4). Two side notes have to be made given the results found:

1. A compensation of the model using additional supports is not successful in this particular case. In Part 3 the final deviation measured to be around 1,5mm, more or less equal to the deviation noticed in part 0. Changing the skewness proved to be more efficient, yielding a parallelism of 0,2mm after post processing.
2. The used stress relief heat treatment leaves some residual stresses in the part as the part is still able to deform after the heat treatment. A full stress relief is expected to leave the part non-deformed after the removal of the substrate plate.

CONCLUSION

Taking into account geometric artefacts of the part that can affect the cooling rate is recommended when setting up the post processing heat treatment. Precise control of the cooling rate during the stress relieve heat treatment in post processing is needed to prevent large scale deformation of the printed part, even when the cross-section of the part would intuitively lead to a non-distorted printed part.

In addition to pre-compensation in the part design, it is a viable solution to add additional machining allowance in areas where deflections are expected. However, not every design will allow that, and some additional cost impact might ensue.

In the quality control and documentation of an additive manufacturing part, the full "thermal history" requires special attention. In defining the successful "AM recipe" for a part, it is important to pay attention to the thermal post-treatment, in order to obtain reproducible results. Hence, it is essential to understand, document in the initial plan, and maintain precisely the 3D printing AND the post-processing processes.

Finally, this case clearly illustrated the need for thermal simulation software that predicts the build process. As of today, such software tools are becoming available. Based on the current results it can be argued that these should take into account the full "thermal history" of the part, hence including any heat treatment after printing.

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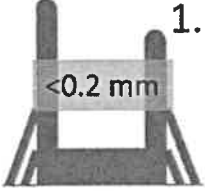
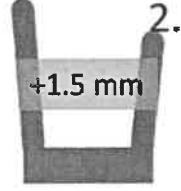
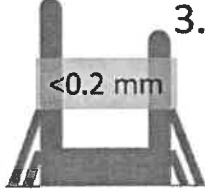
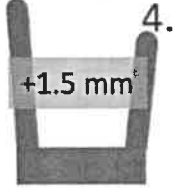
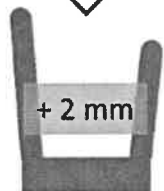
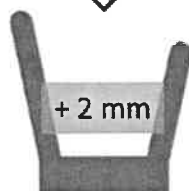
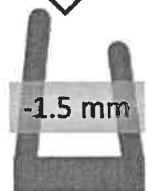
	Initial	Annealed		Stress relieved	
Printed (on build plate)	 0.	 1.	 2.	 3.	 4.
Post-Processed	 -1.5 mm	 + 2 mm	 + 2 mm	 -1.5 mm	 <0.2 mm OK

FIGURE 6 Schematic illustration of post processing results.

LATTICE STRUCTURE TOPOLOGY OPTIMIZATION FOR LIGHTWEIGHT ADDITIVE MANUFACTURED DESIGN: EXPERIMENTAL VALIDATION AND DIMENSIONAL ACCURACY

Lin Cheng¹, Eric Belski^{1,2}, Steve Ludwick^{1,2}, Jason Oskin^{1,3}, and Albert To^{1*}

¹Department of Mechanical Engineering and Materials Science, University of
Pittsburgh, Pittsburgh, PA 15216

²Aerotech, 101 Zeta Drive, Pittsburgh, PA 15238

³Oberg Industries, 2301 Silvertown Road, P.O. Box 368, Freeport, PA 16229-0315

*Corresponding author: albertto@pitt.edu

INSTRUCTIONS

Additive manufacturing (AM) is an advanced process that fabricates components with successive layers of material [1, 2]. The material deposited on each layer is based on the profile of the sliced CAD model. This is an entirely different manufacturing approach as opposed to traditional subtractive manufacturing. Thus, it is possible to manufacture components with complex geometry and multifunctional performance without considering the increment of the cost with the increase of complexity [3-5]. This is more important for aerospace and other applications [6] since a lightweight design with sustainable performance normally means a complex geometric design. The existing design for manufacturing (DFM) rules and guidelines for traditional subtractive manufacturing however, should not be utilized for AM. To take advantage of the AM technologies for lightweight applications, a generic bracket is designed with the methodology that integrates the topology optimization with a lattice structure [7, 8]. Figure 1 shows the L-bracket used for the optimization and fabrication.



FIGURE 1. CAD model of the L-bracket

In this paper, the L-bracket is redesigned with a lattice structure via topology optimization. First, the design requirement for the lattice structure is introduced in the problem statement section. Second, the method to redesign the L-bracket is defined in the lightweight design for L-bracket section. Third, both the simulation and experiment results are analyzed in the validation section. In addition, the deformation distribution is introduced to compare the solid component with lattice structure design. Finally, the conclusion is made for the design of the L-bracket with lattice structure topology optimization.

PROBLEM STATEMENT

Figure 2 indicates the working condition of the bracket. As shown in Fig. 2 (a), the bracket is fixed to the stage with the bolts. This is set as a fixed boundary condition in the finite element analysis (FEA). The load applied to the bracket will be a distributed 50 N force to simulate accelerations experienced during the motion of the stage. The load is distributed over the two faces (Fig. 2 (b) illustrates the faces on which the loading is applied) to account for the footprint of the stage that is normally mounted to this bracket.



a) Fixed Location of Bracket



b) Load Application Faces

FIGURE 2. Working condition of the L-bracket

The material of the bracket is AlSi10Mg. Its corresponding mechanical properties are tabulated in table 1, which is obtained via the testing experiment of the samples printed by the EOS M290 DMLS system.

TABLE 1. Mechanical properties of AlSi10Mg

Item	Density, g/cc	Young's Modulus, GPa	Yield stress, MPa	Poisson's Ratio
Value	2.7	71	95	0.3

Using the properties listed above, the FEA is conducted to simulate the working condition of the L-bracket. Figure. 3 indicates the displacement distribution of the L-bracket. As shown in the figure, the maximum displacement is about 8 μm , which is presented at the end of the long overhang boundary. The requirement for the design is to decrease the mass of the component by 50% while guaranteeing the maximum displacement is not larger than 16 μm . In addition, the design should maintain the original shape of the bracket, which means that the material can only be removed from the inner solid area. To achieve this, the following methodology is introduced to satisfy the lightweight design.

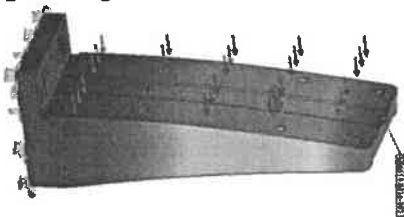


FIGURE 3. Displacement distribution of the L-bracket

LIGHTWEIGHT DESIGN FOR L-BRACKET

Using the lattice structure topology optimization [7], the optimal density distribution is presented in Fig. 4. The red color indicates the larger density while the blue color notifies the lower density. As illustrated in the figure, more material is distributed in the fixed plate and the corner area which connect with the long overhang.

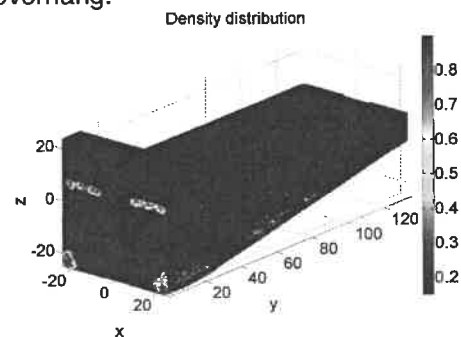


FIGURE 4. Optimal density distribution of L-bracket

The redesigned bracket is shown in Fig. 5. The cubic lattice structure is utilized as the cellular unit to be mapped to the solid component. As illustrated in the figure, the L-bracket is reconstructed with a variable density lattice structure, where the larger density area is constructed with thicker ligament while lower density is represented with thinner ligament.

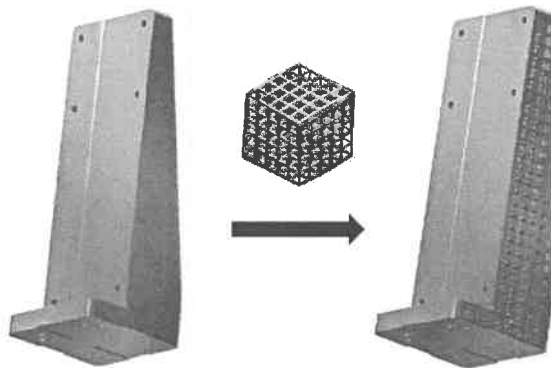
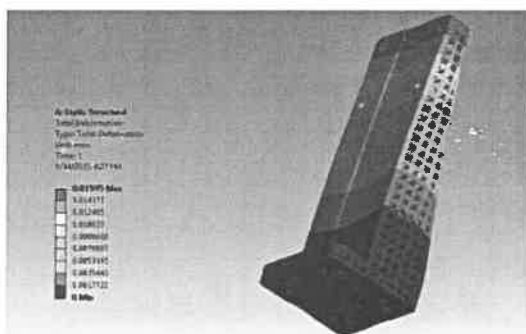


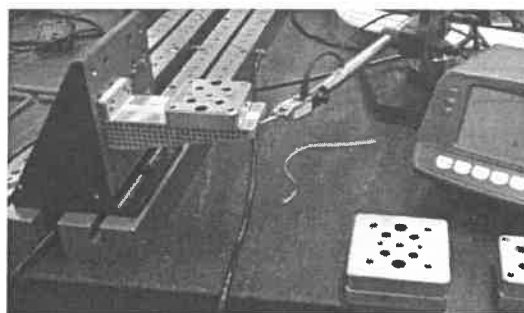
FIGURE 5. Redesigned bracket with cubic lattice structure

VALIDATION

Validation for the redesigned L-bracket is conducted on both numerical simulation and experimentation. Fig. 6(a) gives the distribution of displacement after the simulation, which is calculated on ANSYS 16.1. As illustrated in the figure, the maximum displacement is $15.95\ \mu\text{m}$ while the overall mass of the bracket is 48.45%. Fig. 6(b) illustrates the experiment for the L-bracket conducted by the Aerotech Inc. The stiffness of the solid component obtained via the experiment is $2.224\ \text{N}/\mu\text{m}$ while the stiffness of the optimized bracket is $1.115\ \text{N}/\mu\text{m}$. Note that the difference of the stiffness between the original requirement and the experiment is 0.24%, which is pretty small. The mass removed from the solid component is more than 51.55%, which the difference with the requirement is 3.1%. The detailed results of the experiments are tabulated in Table 2. These results show that the effectiveness of the lattice structure topology optimization for the design of L-bracket.



a) Numerical Simulation



b) Experiment for L-bracket

FIGURE 6. Finite element analysis result for the lattice structured bracket

TABLE 2. Comparison of experiment, required design and the optimized bracket for L-bracket

Item	Solid bracket	Required design	Optimized bracket
Stiffness ($\text{N}/\mu\text{m}$)	2.224	1.112	1.115
Maximum displacement (μm)	8.86	≤ 16	15.95

Next, we compare the deformation of the solid component and the lattice structured component after separating them from the building platform. Fig. 8 shows the solid and lattice structured L-brackets printed by the EOS M290. Note that the right one is the solid bracket while the left one is the lattice structured bracket with variable density. Figures 9 and 10 note the deformation distribution of the solid and lattice structured brackets. As illustrated in the figures and Table 2, the deformation of the lattice structured bracket is more uniform, which standard deviation is $0.0522\ \text{mm}$, while the solid bracket's standard deviation is $0.1039\ \text{mm}$. The results show that the lattice structured component contains less deformation as printed by the EOS M290.

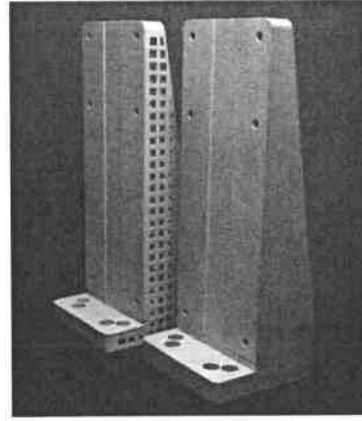
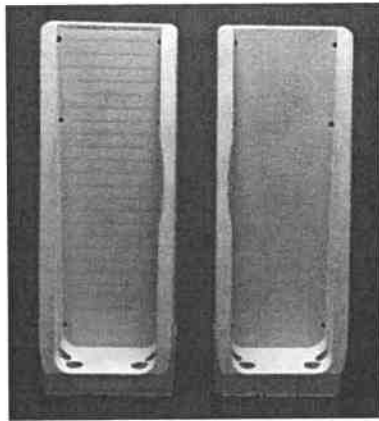


FIGURE 8. L-bracket printed via the EOS M290 with AISi10Mg

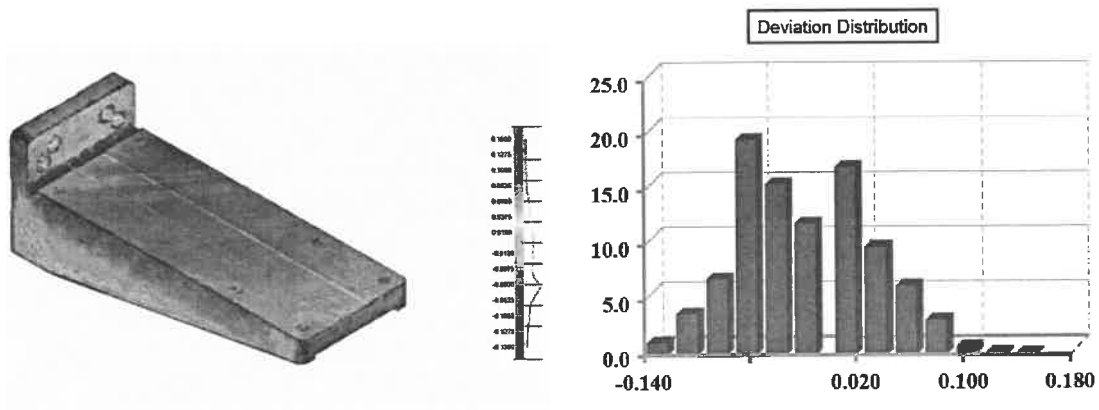


FIGURE 9. Deformation of the solid L-bracket after separation from the build platform

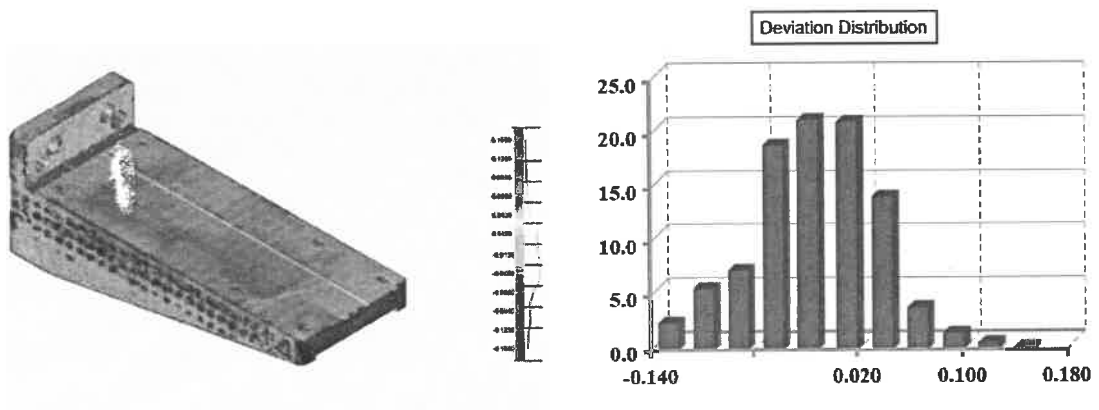


FIGURE 10. Deformation of the lattice structured L-bracket after separation from the build platform

CONCLUSION

In this work a generic bracket is redesigned with the lattice structured topology optimization methodology. Both simulation and experimentation is conducted to verify the efficiency of this type of design. Through the research the following conclusions can be drawn:

- Additive manufacturing is an efficient technique for the fabrication of complex geometry, especially for aero-component.
- The lattice structure is good choice to maintain the original shape of the component while representing the design of topology optimization
- A component designed with a lattice structure has less deformation than the same shape solid component.

ACKNOWLEDGEMENT

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DESIGNING FOR COLOR IN ADDITIVE MANUFACTURING

Eythor R. Eiriksson¹, Andrea Luongo¹, Jeppe R. Frisvad¹,
David B. Pedersen² and Henrik Aanaes¹

¹Department of Applied Mathematics and Computer Science

²Department of Mechanical Engineering

Technical University of Denmark

Kgs. Lyngby, Denmark

ABSTRACT

In this paper we present a color design pipeline for 3D printed or additively manufactured parts. We demonstrate how to characterize and calibrate a commercial printer and how to obtain its forward and backward color transformation models. We present results from our assistive color design tool, allowing for colorimetric accurate prints and visualization of the printed outcome, prior to print. Lastly, we demonstrate our pipeline by accurately reproducing a real physical object.

INTRODUCTION

Due to physical constraints in the 3D color print process, it is impossible to print parts in all colors that we are presented with in the digital domain. The rich saturated colors are simply not available with current printer technology. Failure to acknowledge this limitation results in both disappointment and dull prints. The paper printing industry has been dealing with these problems for decades, still we have yet to see any of the solutions made available for the 3D domain. As of today, no formats supported by the additive manufacturing (AM) printer industry offer CMYK (Cyan, Magenta, Yellow, Black) color inputs, despite it being the native color space of most color printers [1]. Instead, RGB (Red, Green, Blue) is used, as the 3D formats were initially intended for display in RGB based devices, such as computer monitors and televisions.

The transformation from additive RGB colors to subtractive CMYK is handled within the printers hardware. Due to its proprietary nature and lack of color management features, any color related efforts must be made on the 3D model level. A designer is thus designing colored parts in the blind as no relationship exists between the color presented in the computer monitor and the final printed output. Previous efforts focusing on color in additive manufacturing has addressed color placement [2], appearance [3] and attempted to

shed light on this problem by modeling the color conversion, thus allowing for color print prediction [4].

In this paper, we take inspiration from the paper printing industry and apply known methods on the new medium. We present a full end-to-end color design pipeline which allows for color specification. The ability to accurately specify colors and appearance of 3D printed objects has applications ranging from rapid product design, printing prosthetics or dentures seamlessly matching their hosts, and for physical replication of objects.

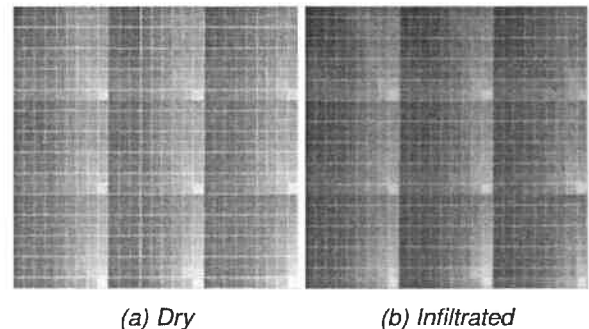


FIGURE 1. Printed color calibration artefacts used in this study.

CALIBRATION

In order to print user specified colors, it is important to understand the color capabilities of the printer. This is obtained by characterizing and modeling the printer's output colors in relation to its input. In this section, we present a calibration method which produces forward and backward color models of the print process. Using the forward model, it becomes possible to pre-visualize the resulting printed color given any input color. Furthermore, if one wishes to print a specific color, the backward model will return the input color required for producing the desired printed color or the closest available color. The calibration procedure is described in the following steps:

Step 1: Calibration Plates

A 3D color plate was generated which has colors sampled uniformly from the RGB color space. A total of 9 samples were made per dimension, resulting in 729 unique colors. We chose this value due to size restrictions of our color measurement system. Ideally, the more samples used in this process the more accurate the characterization and calibration.

Step 2: Print

Two color calibration plates were printed on a Zcorp Zprinter 650 color printer. The plates were thoroughly brushed in order to remove any residual surface powder. One plate was infiltrated with cyanoacrylate whereas the other was kept dry without any infiltration.

Step 3: Measure

Both plates were measured using the multi-spectral imaging system VideometerLAB 4¹. Both CIE Lab D50 and sRGB D65 measurements were obtained for each color patch using an automated algorithm. Figure 2 illustrates the measured range of printable colors possible. It is clear the color gamut is significantly enhanced after infiltration, however at a slight cost of the lighter colors such as white.

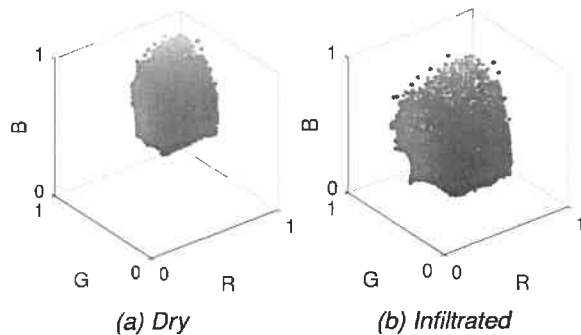


FIGURE 2. Visualization of the printable color range. (Gamut)

Step 4: Forward and backward model

From the empirical measurements relating input colors to measured colors we construct a 3D look up table (3D LUT) of $9 \times 9 \times 9$ elements. The table is then linearly interpolated up to $256 \times 256 \times 256$, thus covering the 8 bit RGB representation. Using the forward lookup table, it is possible to predict measured colors for all input colors. For the backward model a reverse 3D LUT was made of dimensions $256 \times 256 \times 256$ mapping measured col-

ors to its input. For all colors outside of the printable gamut, the nearest neighbor color value was used. This resulted in an 8 bit 3D LUT which returns a color measurement for all possible inputs. By precomputing the LUTs, it becomes possible to efficiently use them as 3D textures commonly used by the computer graphics community.

Step 5: Verification

In order to verify the forward model, a new color plate was printed consisting of random colors. The plate was measured and the color difference metric ΔE_{00}^* between the model and the measurements was computed for each color in the CIE LAB space [5]. The results for the dry and infiltrated model can be seen in Figure 3. For the dry plate we obtain an mean prediction error of $\overline{\Delta E_{00}^*} = 1.3$ and std.dev $\sigma = 0.9$. For the infiltrated plate we obtain $\overline{\Delta E_{00}^*} = 1.5$ and std.dev $\sigma = 1.2$. The increase in standard deviation is as expected since additional variability is introduced in the infiltration process. From Figure 3, it is clear that majority of points lie within the documented just noticeable difference (JND) range from 1 to 5.9 [6, 7]. The prediction model is thus considered satisfactory.

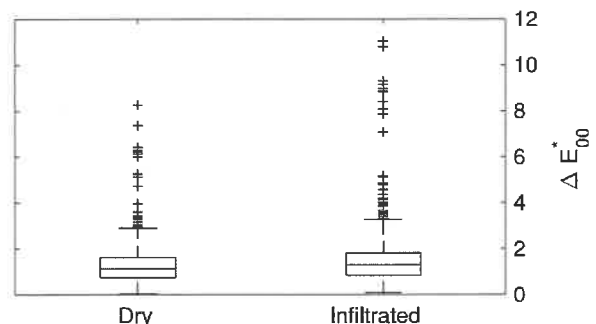


FIGURE 3. Boxplots illustrating color difference ΔE_{00}^* between the measurements and the prediction model. Median value is shown as a line in each box; Box edges are the 25th and 75th percentiles; Whiskers extend to the most extreme data points that are not considered outliers; Outliers are plotted individually.

COLOR DESIGN TOOL

After the printer characterization, we used the calibration data to develop a design tool which enables us to pre-visualize parts before print and to perform color correction if needed. The tool has been developed using the Unity-Game Engine².

¹videometer.com

²unity3d.com

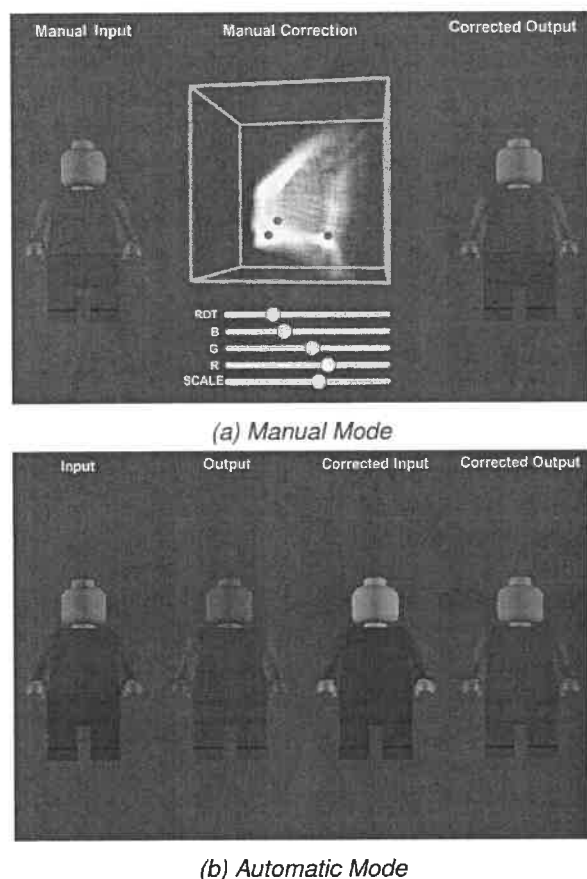


FIGURE 4. Screenshots from our design tool. Showing manual and automatic modes of operation.

Figure 4 shows screenshots captured during operation. The pre-visualization feature makes use of the forward 3D LUT in order to visualize the resulting print of a 3D color model. The reverse 3D LUT is used to perform color compensation on the 3D model in order to account for the change in color due to the print process. Figure 5 shows a toy example for a 3D model of an elephant using the infiltrated 3D LUTs. It is clear that the print prediction of the model (Figure 5b) looks different from the original model (Figure 5a), while after applying the appropriate color compensations the print prediction of the model (Figure 5d) is closer to the original model even though there are still some differences in the colors of the eyes and of the tusks of the elephant.

A good color correction can be done only if the colors of the 3D model lie inside the printable color range. Our design tool provides a feature for visualizing which colors of a 3D model are outside the gamut and therefore are not possible to

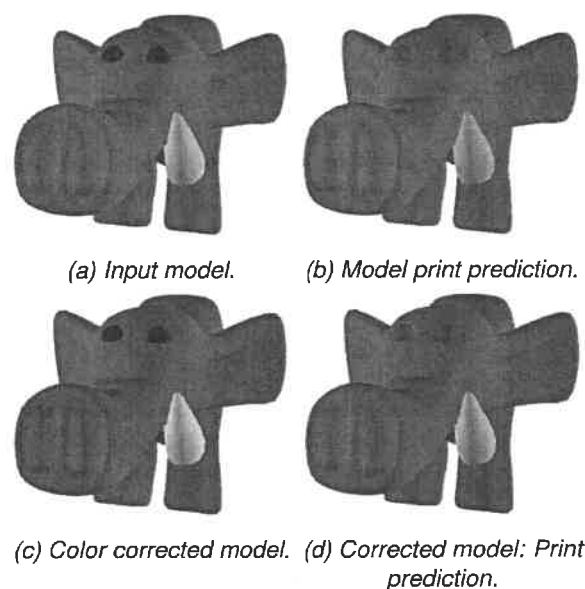


FIGURE 5. Design tool results (Infiltrated LUTs).

correct by using the measured 3D LUTs. Figure 6 shows the elephant model using the infiltrated 3D LUTs where the colors of the eyes and tusks do not lie inside the printable gamut shown in Figure 2b. As result, they are highlighted with a red-dish color. For each color that is not printable, the reverse 3D LUT provides the nearest printable color, and while in some cases, e.g. elephant's tusks, this approximation might give acceptable results in other cases, e.g. elephant's eyes, the corrected color is far away from the original color. In terms of colorimetric accuracy, this might not be acceptable. However, if the goal is to produce visually pleasing results, the tool allows the user to maintain the relative relationship of colors.

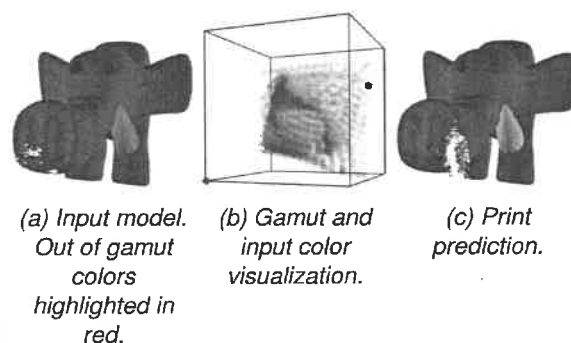


FIGURE 6. Design tool output using infiltrated LUTs. Model colors are marked as red dots, whereas the printable region is depicted in blue. On the model, the out-of-gamut colors are highlighted in red, alerting the user that these colors will not be printed correctly.

In order to correct the colors outside of the gamut, our tool gives the possibility to manually change the colors of the model until they all lie inside the printable color range. Then, by performing an automatic compensation based on the forward and reverse LUTs, we can visualize the print prediction of the manually-corrected 3D model. An example of this feature can be seen in Figure 6, where we see a 3D input model with the highlighted out-of-gamut colors, and the resulting print prediction of the corrected 3D model. Additionally the RGB color space is visualized dynamically where the printable gamut (blue region) and the colors included in the original 3D model (red dots) are shown. This gives the user a dynamic visual feedback of how many colors of the input model are lying outside of the gamut and therefore not printable.

The manual color correction is performed by scaling and translating the red dots representing the colors of the input model until they fit inside the region covered by the gamut. This is done interactively using sliders. The colors that are manually placed inside the gamut become printable and the reverse and forward LUTs show dynamically the color correction print prediction of the model as close as possible to the manually corrected input model. A designer thus has full control over the colors in a 'What you see is what you get' (WYSIWYG) fashion, greatly simplifying the design process.

EXAMPLE: PART REPLICATION.

To further evaluate our model and design tool, we measured a sample of cork in order to create a 3D printed replica. Figure 7 shows results from our design tool which given an input 3D color model (Figure 7a), visualizes its resulting print (Figure 7b). The tool then produced a corrected version (Figure 7c) where the infiltrated reverse 3D LUT was used to compensate for the change in color during the print process. For user verification the corrected print prediction is shown in Figure 7d.

The corrected color model shown in Figure 7c was printed on a Zprinter 650, allowed to dry, thoroughly brushed and then finally infiltrated with cyanoacrylate. In parallel, the cork was printed with and without color compensation in various sizes. The final printed output can be seen in Figure 8 where the cork replica with color compensation closely resembles the actual object, whereas the cork without compensation is observably darker.

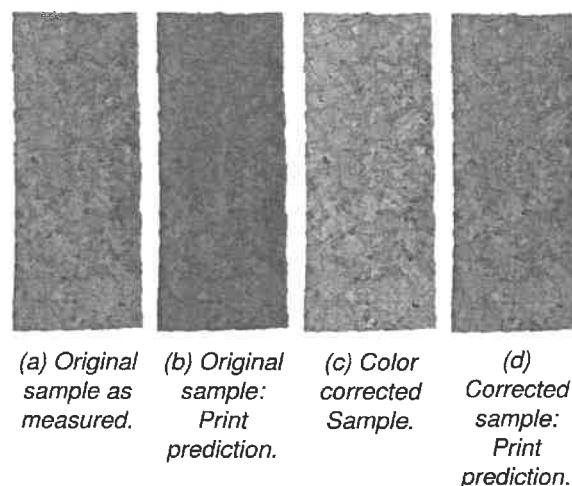


FIGURE 7. Results from our color design tool. Demonstrating pre-visualization of parts prior to print. c) shows the color corrected sample as would be used as input to a print process. d) shows the end result, which accurately matches the original sample a).

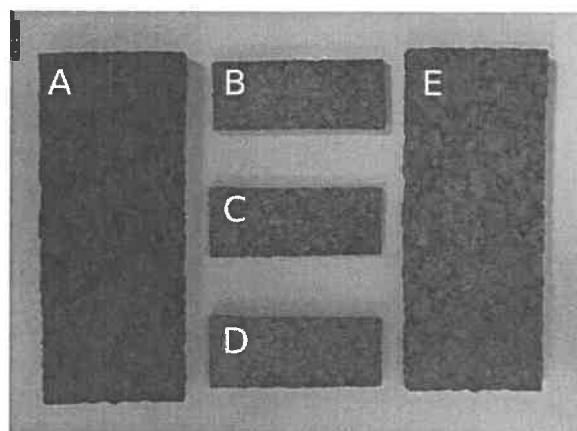


FIGURE 8. Final printed results. A: Enlarged printed cork without color correction. B & D: Printed cork with color correction. C: Original cork sample. E: Enlarged printed cork with color correction.

DISCUSSION

The process described in this paper has been implemented on an industrial color 3D printer. We demonstrated a successful calibration procedure and a method to verify its validity. The results show that accurate color predictions and calibration can be obtained with color difference error averaging comfortably under the JND metric threshold. We presented preliminary results from our

color design tool that can pre-visualize parts before print as well as apply automatic color compensation based on the calibration models. Furthermore, it offers manual means of correcting for color whilst providing visual feedback to the user in the form of a dynamic print prediction and 3D gamut plot. Lastly, we show an example where we produce a 3D replica of a real physical object. Our results show that with color compensation and careful modeling of the print process it is possible to print accurate color replicas closely matching the original object's appearance. With the help of our pipeline, it is thus possible to specify printed colors accurately. This enables the printing of colored prosthetics or dentures seamlessly matching their hosts as well as delivering true and accurate prints of designs during product development.

The design tool will be made publicly available in the near future.

ACKNOWLEDGEMENT

The work of this paper was supported and made possible by the Manufacturing Academy of Denmark (MADE).³

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³www.made.dk

PRECISION LOCATING OF ADDITIVELY MANUFACTURED PARTS USING EMBEDDED KINEMATIC COUPLINGS

Ryan Wade Penny and A. John Hart
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

INTRODUCTION

The application of Additive Manufacturing (AM) to precision engineering requires the derivation of design principles for precision locating. This is essential to accurate assembly of components made by AM, as well as locating AM components for precision machining and finishing operations that are often necessary for final use. Moreover, the immense flexibility of AM is challenged by limitations to surface finish and overall part accuracy, making it important to derive process-specific guidelines for the incorporation and use of traditional locating features in AM, as well as for derivation of potentially new designs [1].

As an initial step toward this goal, here we study the fabrication and performance of ball-groove kinematic couplings (KCs), which are widely used due to their high repeatability arising from near-ideal contact at six points (Fig 1a). Critical to KC performance is understanding of the geometric accuracy, friction, and elastic-plastic deformation necessary to create couplings that mate repeatably and have adequate stiffness for their intended use [2][3].

Specifically, we evaluate Fused Deposition Modeling (FDM) with ABS (Acrylonitrile Butadiene Styrene) plastic as a means of fabricating KCs, and quantify the stiffness and repeatability achieved. Design of kinematic features for this AM process is particularly challenging for two reasons. First, FDM is a layerwise process in which a part is sliced into a plurality of 2D layers, each with a thickness of $\approx 0.1 - 0.3 \text{ mm}$ for this material [4]. This quantization process reduces curved or out of plane features to a stair-step like approximation. Second, the low stiffness, low strength, and anisotropy of FDM ABS ensures that the contacts will plastically deform under most practical loads.

SINGLE PAIR TESTS

First, we measure the elastic-plastic behavior of single sphere-groove interfaces to provide a

basis for interpreting the results of repeatability experiments on full couplings. These tests are performed using a universal testing machine to record force-displacement curves as a single sphere-groove combination is cyclically loaded to a prescribed peak force. Spherical components were designed around a 25.4 mm nominal diameter, with truncated vee components sized to match (Fig. 1b). Initial tests used a single AM sphere or vee, indented using a hardened steel counterpart. These trials both provide insight to the performance of AM parts in a workholding application and enable more intuitive analysis of deformation mechanics. Results from indentation tests on AM on AM parts are also presented, which are more relevant to rapid prototyping and short run manufacturing of precision assemblies.

A typical cyclic force-displacement curve is presented Fig. 2; these data were recorded as an AM sphere was loaded to 100 N with a steel vee. The normal stiffness of the coupling pair is simply determined by the slope of the loading curves, which are plotted in red in Fig. 3. The measured stiffness of $1363 \text{ N}/\mu\text{m}$ is very close to the value of $1370 \text{ N}/\mu\text{m}$ obtained using Hertzian contact mechanics [5]. Moreover, the predicted contact stress ratio is greater than unity, implying that plastic deformation of the coupling will occur. Subsequent cycles show that stiffness approaches $2400 \text{ N}/\mu\text{m}$ as the surface deforms and the contact area enlarges.

Next, the energy dissipated in a given cycle is represented by the area between the curves generated as the specimen is loaded and unloaded. The unrecovered energy, quantified for this trial in Fig. 4 (red dots), is expended by plastic deformation the specimen, friction, and viscoelastic dissipation arising from short range molecular motion [6]. Dissipation is higher for the first several cycles as the surface texture of the AM part is deformed, then approaches a constant asymptote representative of frictional and viscoelastic losses. Viscoelastic behavior is the largest driver

of hysteresis in the coupling, which has been identified as key factor in repeatability [7]. The deformation sustained over 10 cycles is shown in Fig. 1d, which is faintly visible even with the aid of a microscope.

Figures 3 and 4 also provide results for specimens that have been printed in an orientation out of plane by $+90^\circ$ about either the $+X$ or $+Y$ direction. The spheres proved stiffest printed upright, and lower stiffness is correlated with increased hysteresis.

These trends repeat for specimens loaded to higher peak forces, as listed in Table 1. A stiffness of $2950\text{ N}/\mu\text{m}$ is predicted for the first cycle of a specimen loaded to 1000 N ; again in excellent agreement with the experimental result of $2884\text{ N}/\mu\text{m}$ for an AM upright sphere. Once broken in, the coupling's stiffness is greater than $5000\text{ N}/\mu\text{m}$ at the cost of substantial deformation from the original spherical profile, as captured in Fig. 1e.

Stiffness of AM vee-steel sphere coupling pairs have also been included in Table 1, again for forces of 100 N and 1000 N . Interestingly, this combination substantially underperformed both as compared to the theoretical stiffness of the coupling and their AM sphere counterparts. This difference is unexpected; Hertzian contact theory for conventional surfaces does not differentiate which material forms the sphere or plane [8]. Heavily loaded specimens show crazing in locations well removed from the contact patch, suggesting that this discrepancy results from the geometry surrounding the contact planes. Specifically, stress concentrations in the corners of the truncated vee are evident, arising from undesirable deformation in these regions. A final point of contrast from the AM sphere results is that vees printed $+90^\circ$ out of plane about the $+X$ direction proved stiffer than the other orientations tested.

Last, we measured coupling stiffnesses in which both components have been additively manufactured by FDM. Components were printed in their stiffest orientations as identified above and cyclically loaded to either 100 N or 1000 N . As seen in Table 1, the coupling stiffness is less than the AM vee/steel sphere trials, which serve as an upper bound for the expected stiffness of the coupling. The reduced rigidity is simply explained by the complex interaction of surfaces with large amplitude, structured surface texture. Figure 1f

is an image of the deformation sustained from the 1000 N trial, showing a clear imprint from the counterpart, rather than the more uniform deformations seen in the other trials. This checkered texture implies many small regions of high contact pressure, thereby reducing the rigidity of the coupling.

FULL COUPLING REPEATABILITY

Guided by our coupling stiffness measurements, we performed an experiment to assess the repeatability of AM KCs. Central to these tests was defining a procedure to break-in the couplings. In any practical application, a coupling would be preloaded upon installation, then subject to additional dynamic loading under use. It is then necessary to break-in the coupling at forces greater than the anticipated worst-case loading, such that plastic deformation is minimized over the coupling's service life. To simulate such a real-world application, we assembled and loaded couplings three times to a force 133% larger than the test load. Break-in was always preformed against the mate used to assess repeatability; a test of AM spheres against AM grooves would have these parts broken-in against each other, for example.

After break-in, repeatability was measured using a Wenzel LH108 Coordinate Measuring Machine (CMM). The bottom half of the coupling was rigidly secured to the CMM, and a series of datum features were identified. Then the top half of the coupling was installed, tightened with a torque wrench to place the test load across each sphere-vee pair, measured with respect to the datum features on the bottom part, and finally disassembled. Three such measurements were taken for each trial configuration. The standard deviation of the X, Y, and Z displacements were then added in quadrature to determine the net repeatability of the fixture.

Repeatability measurements, presented in Table 2, show that repeatability of $35\text{ }\mu\text{m}$ or better is readily attainable using deformed couplings. Existing literature suggests that coupling repeatability should be roughly equal to the magnitude of surface roughness present on the contact surfaces [9] [10]. Clearly, the deformed surfaces yield better performance than their original $\approx 170\text{ }\mu\text{m}$ surface texture would suggest. Moreover, the more lightly loaded specimens, which feature greater residual surface roughness, show superior repeatability. One may then conclude that lower friction, viscoelastic loss, and smaller

TABLE 1. AM KC pair stiffness for a number of test cases.

Spheres	Veels	AM Build Orientation	Test Load	Cycle 1 Stiffness	Cycle 10 Stiffness
AM ABS	Steel	Default	100 N	1363 N/mm	2384 N/mm
AM ABS	Steel	+X	100 N	1190 N/mm	1927 N/mm
AM ABS	Steel	+Y	100 N	1030 N/mm	1559 N/mm
AM ABS	Steel	Default	1000 N	2884 N/mm	5416 N/mm
AM ABS	Steel	+X	1000 N	2282 N/mm	4732 N/mm
AM ABS	Steel	+Y	1000 N	2103 N/mm	4990 N/mm
Steel	AM ABS	Default	100 N	915 N/mm	1316 N/mm
Steel	AM ABS	+X	100 N	835 N/mm	1478 N/mm
Steel	AM ABS	+Y	100 N	836 N/mm	1080 N/mm
Steel	AM ABS	Default	1000 N	2367 N/mm	3067 N/mm
Steel	AM ABS	+X	1000 N	2468 N/mm	4273 N/mm
Steel	AM ABS	+Y	1000 N	2366 N/mm	3317 N/mm
AM ABS	AM ABS	Default, +X	100 N	537 N/mm	963 N/mm
AM ABS	AM ABS	Default, +X	1000 N	1687 N/mm	2612 N/mm

contact area are more important factors than the greater surface averaging achieved through higher force. Finally, fully AM couplings feature repeatability on par with mating AM parts against steel counterparts. This result is somewhat counterintuitive, because the AM parts are much more compliant than plastic-steel couplings and would be expected to benefit from deformation against an ideal counterpart.

Also of note, a load of 1000 N per coupling pair between AM vees and steel spheres proved sufficient to crack the AM specimen. This clearly had a disastrous effect on the repeatability of the coupling. Failure was not expected on the basis of the indentation tests, in which no specimens showed evidence of catastrophic cracking. However, this does serve as a confirmation of the prior observation that the spherical geometry better handles the stresses developed in the material surrounding the locating features.

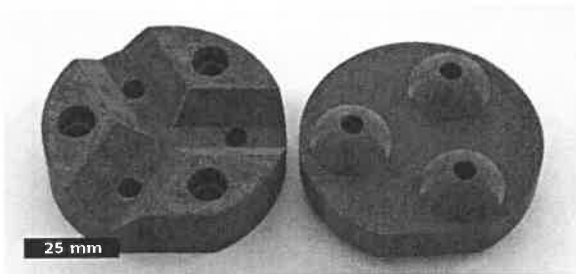
PRECISION LOCATION OF OPTICAL ELEMENTS

Finally, we illustrate the utility of AM kinematic features in the precision location of optical elements. We present a Keplerian refracting telescope, consisting of a fully 3D printed assembly that positions a pair of replaceable glass lenses. As each lens is constrained by a removable lens mount, one may change the magnification ratio of instrument by changing the combination of lenses installed. Fabrication of the lens mounts is particularly well suited to AM, as each must be customized to match a specific outer diameter and

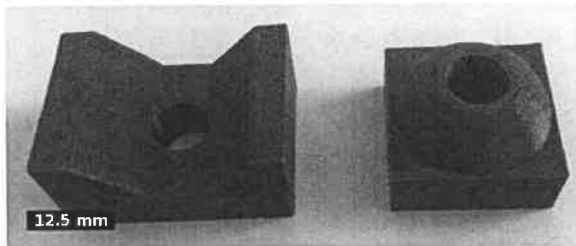
focal length. Likewise, AM permits integration of locating features, magnetic preloading, and light seals into a monolithic central fixture. This optical topology requires that any two lenses installed must be separated by the sum of their focal lengths; furthermore, optical quality improves as this sum is increased for a given magnification ratio [11]. These considerations suggest an optomechanical design in which lenses are separated from their alignment and attachment features to the greatest degree possible, thereby maximizing the optical length of the instrument. KCs are an ideal way to locate the displaced lenses, as the small angular deviations possible about a pinned interface would manifest as large displacements of the lenses, thereby negating the benefit of a long optical path.

Our instrument, shown in Fig. 5a, features a 50 mm diameter, 250 mm focal length objective that may be paired with eyepiece lenses to achieve 10× and 25× magnification. This telescope features a comparatively low f-number ($f/5$) for instruments of its class; achieving this level of performance requires mechanically locating the lenses to within 250 μm for acceptable image quality. As inferred from the blurring of the serifs in Fig. 5c, we have achieved such a level of precision despite having the lenses separated by 275 mm and two KC interfaces (Fig. 5b). This demonstration highlights the potential of AM for building functional precision assemblies with embedded kinematic couplings.

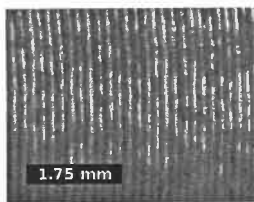
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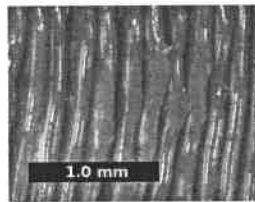
(a) Full coupling set.



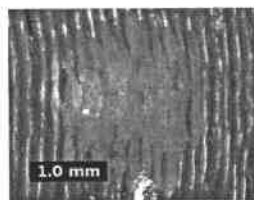
(b) Indentation test specimens.



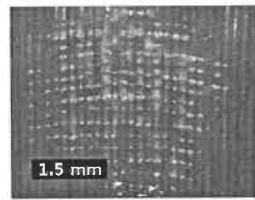
(c) Undeformed AM sphere showing typical surface texture.



(d) AM sphere showing surface deformation after being loaded to 100 N with a steel sphere. Six layers show evidence of deformation.



(e) AM sphere showing surface deformation after being loaded to 1000 N with a steel sphere. Fourteen layers have been deformed. Note the relative size of the layers as compared to (b).



(f) AM vee showing surface deformation after being loaded to 1000 N with an AM sphere. Note the vertical bands in the contact patch, corresponding to the surface texture of the spherical specimen.

FIGURE 1. AM indentation test specimens.

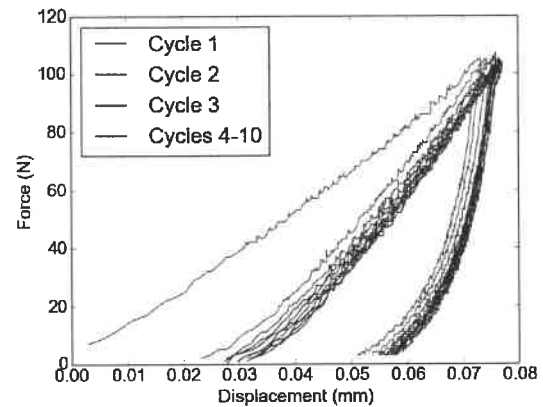


FIGURE 2. Cyclic force-displacement curves for an AM sphere loaded with a steel vee to 100 N . Curves asymptotically approach equilibrium as plastic deformation slows.

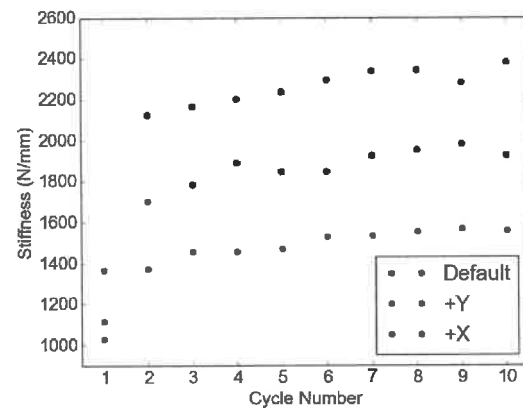


FIGURE 3. Measured stiffness of an an AM sphere cyclically loaded with a steel vee to 100 N .

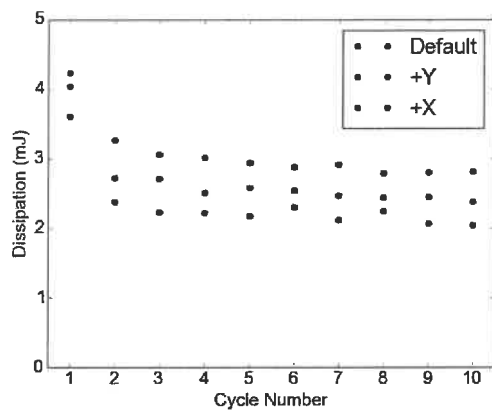
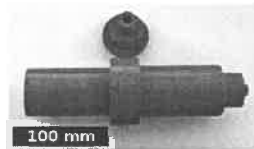


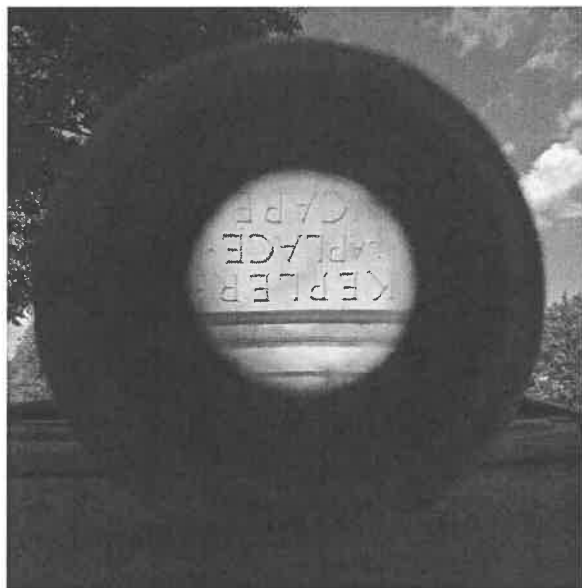
FIGURE 4. Energy dissipated by an AM sphere cyclically loaded with a steel vee to 100 N.



(a) Fully assembled telescope with 25 $\times$ eyepiece installed. 10 $\times$ eyepiece is also pictured.



(b) Telescope kinematic couplings. Magnets provide preload across the coupling.



(c) Image taken through the telescope at 10 $\times$ magnification. Inverted images are characteristic of Kepler's design.

FIGURE 5. AM telescope with kinematic couplings.

Powder Bed Layer Geometry

Michael McGlaufflin, Shawn Moylan
Engineering Laboratory
National Institute of Standards and Technology¹
Gaithersburg, MD, USA

ABSTRACT

This paper investigates the measurement of machine performance errors associated with the powder bed geometry of a commercially available laser additive manufacturing (AM) machine. The methodology is based on existing ISO and ANSI standards as employed in computer numerically controlled machining centers. The paper describes the design of the tests and sign conventions. A discussion is presented on which error sources can affect both the powder layer thickness and part geometry. Finally, it is shown that these existing standards can be applied Laser Based Powder Bed Fusion (LPBF) machine metrology and includes a discussion of where modifications may be necessary.

INTRODUCTION

LPBF type machines employ a composite build process. Four discrete processes interact at various times throughout the build to achieve final part specifications. They are: creating the powder layer by the recoater arm, positioning of the workpiece by the build platform, positioning the laser beam by scanner optics, and controlling the speed and power of the laser through process parameters. The first three of these are subject to error motions that can affect final part geometric errors and build quality. Build platform and optical path errors contribute directly to geometric part errors, while errors in the motions of the recoater arm and build platform can affect powder layer thickness, thickness variation and flatness. Process parameters, like laser power, scan speed, etc., govern the build process, and are input by the user and controlled by the machine software. These parameters are optimized for a nominal layer thickness and powder density.

Current AM machine verification procedures call for building a test artifact which is independently measured on a coordinate measuring machine (CMM). Geometry errors, if any, are then corrected by making software corrections to scaling. Individual machine manufacturers have their own specific artifact designs and currently no standardized artifact design has been designated. While this is a useful procedure for acceptance, it falls short in differentiating the source(s) of the error(s). Research at the National Institute of Standards and Technology on test artifact design has shown geometry errors in the range of $30\text{ }\mu\text{m}$ [1]. As LPBF technology advances, improvements in accuracy and repeatability must be realized through a more comprehensive process. Reducing the errors of the recoater arm, scanning mirrors and build platform may ultimately contribute significantly to advances in accuracy.

National and international standards exist which appear to meet many of the requirements for additive machine tool metrology. Specifically, ISO 230-2 [2], ANSI B5.54 [3], and ISO 230-3 [4] contain numerous tests and procedures that at first principles should quantify many of the error motions for AM equipment [5]. Tests were conducted to evaluate the effectiveness of these standards for a commercially available LPBF machine using well established metrology equipment such as a displacement laser interferometer, capacitance probes, and precision levels. Measurements were carried out at ambient temperature and, when practical, compared with similar measurements performed at the machine's operating temperature of 80°C .

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NOMENCLATURE AND SENSITIVE ERRORS

Errors associated with an axis can be described using a simple three letter terminology for each of the Six degrees of freedom. For example, a linear error of the Z-axis in the Y direction (straightness) can be denoted as E_{YZ} . Likewise, an angular error around X in the Z axis would be described as E_{AZ} . This descriptive terminology works well for machine tools but is complicated by LBPF technology. (FIGURE 1)

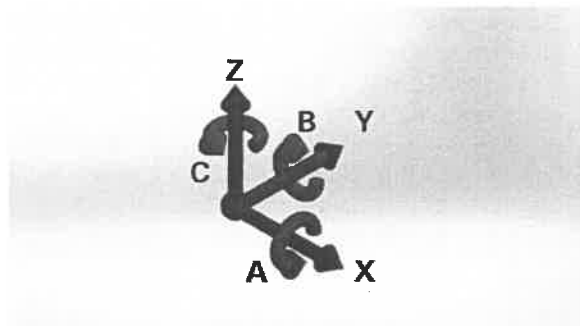


FIGURE 1: Axis Designation

While it can be argued that the motion of a typical recoater arm is in the X direction, it by current definition is not the X axis [6]. X and Y axes are orthogonal to the Z axis, which is defined as "normal to the layers," so the X axis is likely more closely tied to laser spot motion. As such, for the purposes of this paper and subsequent discussion, the authors have chosen to use the letter R to designate error motions of the Recoater Arm.

Powder layer geometry is determined by the interaction of the recoater arm and the build platform. The recoater arm can be viewed as a rigid body in that the motion is repeated in the same plane throughout the build process. The build platform motions are comprised of small incremental changes as each layer is completed. The powder reconstitution process (see FIGURE 2) involves lowering the dispenser platform, lowering the build platform, moving the recoater arm to the far right location, raising the dispenser to its original position plus an amount determined by process parameters, raising the build platform to a position 0.02 mm (equal to one layer thickness) below the previous level then moving the recoater arm to its far left position; thus spreading a layer of powder over the build plate.

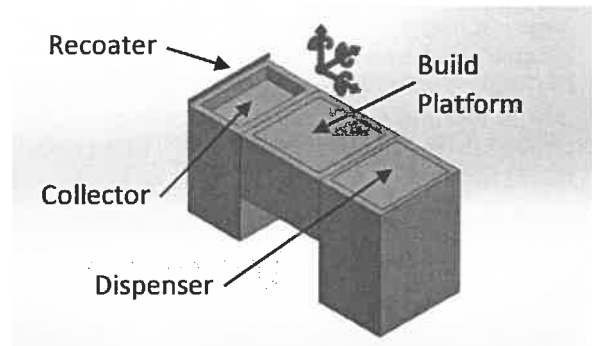


FIGURE 2: Chamber Layout of the test machine

The combined error motions of both the recoater arm and build platform determine deviation in the powder layer geometry. Error motions of the recoater arm directly affect the powder layer while build platform motions can affect both powder layer and part geometries. As the recoater arm is spreading the next powder layer, only two error motions contribute directly to variations in the powder layer. Those motions are: straightness in the Z direction, or E_{ZR} and angular error in A, or E_{AR} . The recoater likely has errors in the other four directions, but they do not influence layer thickness. All six error motions of the build platform have some effect on the build. E_{YZ} , E_{XZ} , and E_{CZ} only affect part geometry, not layer thickness. E_{AZ} , E_{BZ} and E_{ZZ} affects both the part geometry and the layer thickness.

TESTS AND ANALYSIS

Data is presented here as evidence of the efficacy in applying machine error equipment and procedures to a new technology. No inferences should be drawn as to the performance of the AM machine being tested.

In keeping with ISO suggested procedures, all measurements were taken between the recoater arm the, "(tool)" and the build platform (the, "part"). To accomplish this a Metrology Adapter (see FIGURE 3) was designed which was attached to a convenient rectangular bar placed by the manufacturer for aligning the build plate prior to starting a build. This adapter held the capacitance probes for Recoater Arm measurements, a target for environmental tests, the reference level, and optics for laser displacement measurements.

Environmental Temperature Variation Error (ETVE) quantifies the effect of thermal changes in the machine structure caused by the environment and start-up of a machine tool. A precision target (see FIGURE 3) consisting of two

gage spheres is mounted to the metrology adapter, and a nest of five capacitance probes to the build platform. Relative changes in location due to thermal expansions can be recorded and analyzed to show both linear and angular displacements.

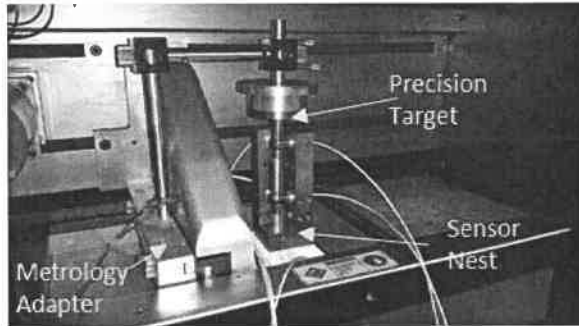


FIGURE 3: Instrument Layout for ETVE Measurements

For the purposes of this study the test consisted of three elements; machine off, machine on (computer and mechanical systems), and build plate heating. The test spanned a period of 8 hours.

Results are shown in FIGURE 4. Surprisingly, the plot shows what is best described as a step change behavior as opposed to the expected exponential effect of thermal saturation.

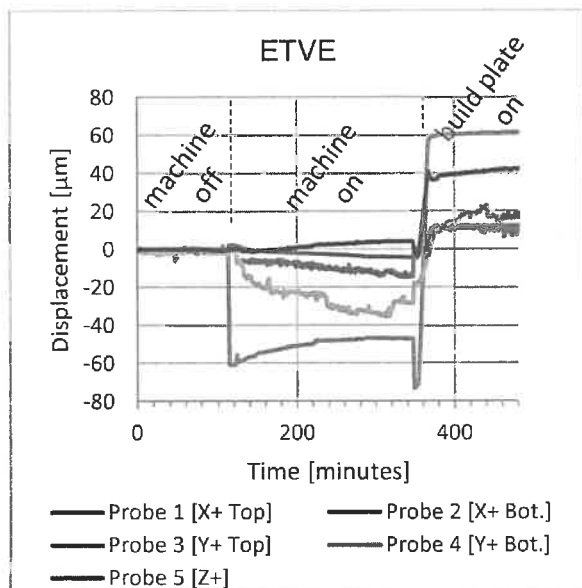


FIGURE 4: ETVE measurement results

Errors in linear axis motion

For linear motion tests, it is important to note that bidirectional axis motions were not employed during this study for two reasons. First, the build process is a series of unidirectional motions. In the case of the recoater arm, the powder is spread only as it traverses from right to left. Secondly, the build platform nominally moves in a negative Z direction as the build progresses. Notably the manufacturer has built a reversal motion into its positioning sequence. As the platform repositions in the negative direction it first overshoots the desired location by approximately 1 mm then moves in an upward, or positive motion to its target. This motion only occurs as the build platform moves in the negative, or downward direction.

Another fact worth noting is that all tests were run with the build chamber door open. With the exception of laser displacement tests it is possible to run most tests with the door closed by routing wiring through access ports.

Capacitance Probes were also utilized to measure Recoater Arm errors E_{ZR} and E_{AR} . The probes were oriented downward in two locations in the metrology adapter 175 mm apart. A build plate was bolted to the Build Platform to act as a reference artifact. Separate CMM measurements were conducted on the plate to remove artifact errors from the data.

Data were taken as the recoater arm traversed from right to left at 20°C. Results are shown in FIGURES 5 and 6.

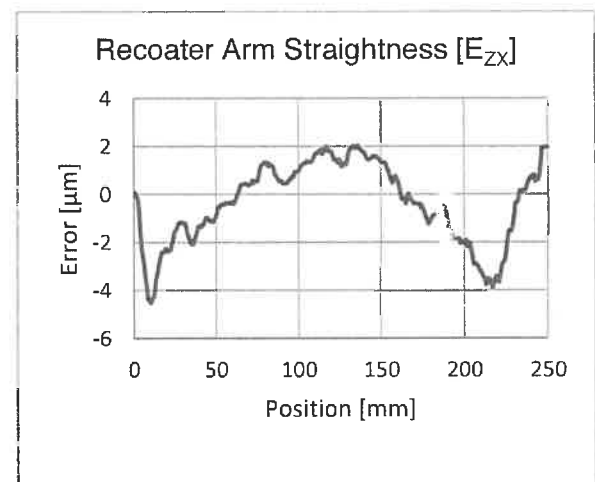


FIGURE 5: Recoater Arm straightness in Z

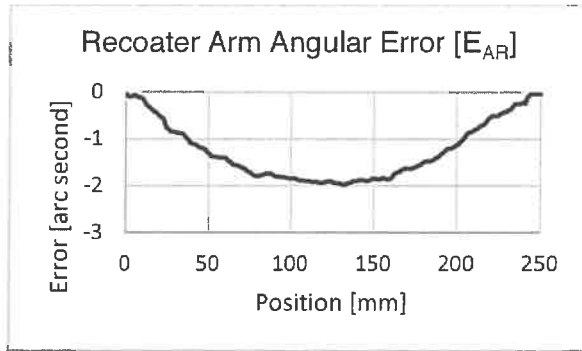


FIGURE 6: Recoater Arm error in A

Interferometer tests for position and angular errors A and B of the build platform motion (Z-axis) were conducted throughout the z-axis range. Interferometer optics were mounted to the metrology adapter and target optics to the Build Platform (see FIGURE 7). The full axis travel was measured in 10 mm increments and four randomly chosen locations (20, 75, 125, and 187 mm) were selected for 20 μm (the nominal powder layer thickness) tests over a 1 mm range. Results are shown in FIGURES 8, 9, and 10.

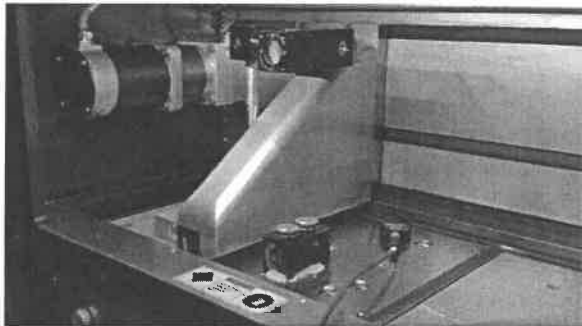


FIGURE 7: Instrument layout for laser measurements of the Build Platform axis

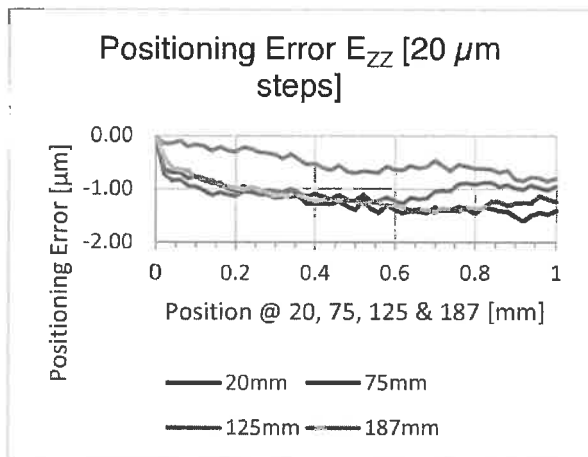


FIGURE 8: Random location 20 μm steps

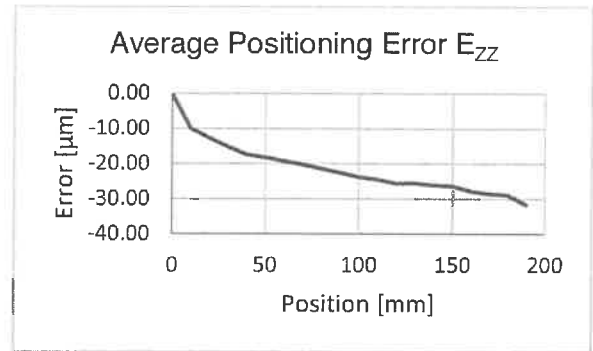


FIGURE 9: Build platform positioning error

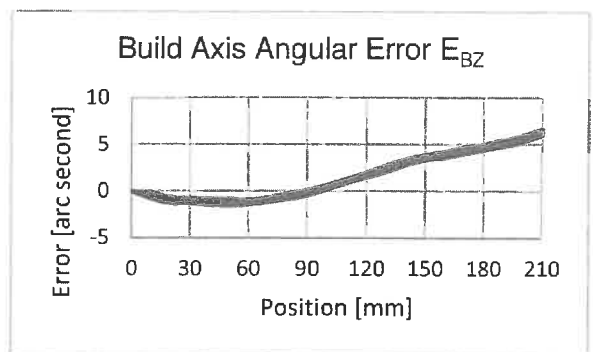


FIGURE 10: Build Platform rotation in B

Precision Differential Level Measurements for build platform rotations A and B were conducted for both applicability and comparison to laser results. A reference level was placed on the Metrology Adapter (see FIGURE 11), located at the far left position for clearance reasons, and the measurement level on a thermal isolation block on the Build Platform. This measurement series provided the best opportunity for taking data at 80 $^{\circ}\text{C}$. While the addition of the thermal block reduced the range of motion, it was considered necessary to protect the equipment. Results can be seen in FIGURES 13 and 14.

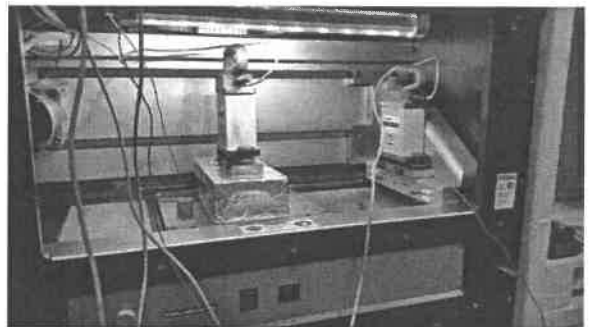


FIGURE 11: Instrument Layout for Differential Level Measurements

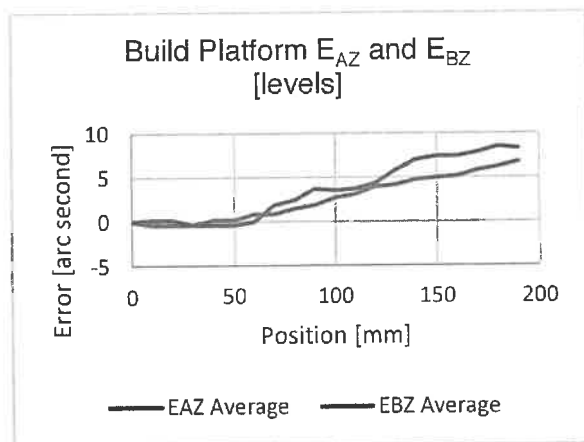


FIGURE 13: Build Platform angular errors

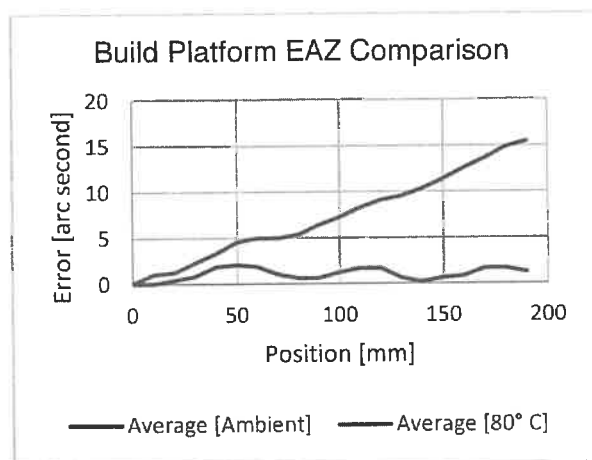


FIGURE 14: Comparison of angular error A at ambient and operating temperatures

Estimated uncertainty calculations [2, 3] are $U_{\text{Expanded}} = 5.91 \mu\text{m}$ ($k=2$) for the laser displacement measurements, $U_{\text{Device}} = 0.014 \mu\text{m}$ capacitance probes, and $U_{\text{Device}} = 0.4$ arc seconds for the Differential Levels.

DISCUSSION

As can be seen in the previous section, we were able to complete all of the required measurements without major changes from the methods prescribed in the standards. The largest required change is the selection of target positions for the Z-axis. ISO 230-2 [2] suggests target positions derived from an equation resulting in a stratified random pattern of targets that avoids complications of periodic error. ANSI B5.54 [3] does not suggest specific targets, but does require selection of target positions over the full travel range of the axis. Both standards require a minimum of five targets following a specific serpentine test cycle. For testing the

errors in positioning for layer thickness, the obvious target interval is equal to the nominal layer thickness. We wanted to test throughout the entire range of travel for the axis because positioning error may vary throughout, but testing a target interval of $20 \mu\text{m}$ over the entire range (210 mm) is impractical. We arbitrarily chose four areas in the range of axis motion to test $20 \mu\text{m}$ intervals over 1 mm travel. For standardization, a more systematic approach to choosing the areas to test at layer thickness intervals may be desired. Further, the appropriate number of areas to test at these finer intervals may require more thought. The parameters described in the standard for the ETVE test [3] are logical for the typical thermal saturations seen in machine tools, but the data seen here in FIGURE 4 may suggest that the time intervals for testing could be altered for testing LPBF machines. On one hand, the displacements seem to reach steady state rather quickly. On the other hand, an AM build may last days. More data, analysis, and thought are needed before any specific recommendations can be reached. It is also worth noting that our study ignored one test discussed in ISO 230-3. Thermal displacement due to axis motion was deemed insignificant considering the slow infrequent motion of the Recoater and Z-axis during a build and the fact that the build platform heating to 80°C is likely much larger than any heat generated by motion.

Not surprisingly, experimental results suggest that temperature plays a large role in the positioning error as well as the measurement of positioning error. Measuring at the elevated operating temperature would likely be desired to give a better estimation of how the machine performs during actual operation. However, we found that some measurement equipment, the laser interferometer specifically, did not work when the build platform was heated to this temperature.

Measuring at higher temperatures has a large impact on measurement uncertainty. Because the laser interferometer would not work properly, a device with larger uncertainty would be needed to perform the measurement. Further, the standards state that if measurements are carried out at temperatures other than 20°C , the relative expansion between the machine and the measurement device must be compensated. This task requires knowledge of the coefficients of thermal expansion, which also have uncertainty. If we assume an uncertainty in coefficient of

thermal expansion of $2\text{ }\mu\text{m/m }^{\circ}\text{C}$ (the “typical range” given in ISO 230-2), the expanded measurement uncertainty when the build platform is at $80\text{ }^{\circ}\text{C}$ is approximately $0.07\text{ }\mu\text{m}$ when the measurement length is 1 mm , as is the case for the finer interval measurements. However, when testing over the entire range of Z-axis or Recoater axis motion ($\approx 200\text{ mm}$), the expanded measurement uncertainty increases to approximately $14\text{ }\mu\text{m}$, more than half of a layer thickness and approximately half of the total deviation observed here. Note that these values do not account for uncertainty in the measurement of temperature, nor do they account for uncertainty in the measurement device, both of which may increase with increasing temperature.

Another minor complication, the challenge of aligning the measurement device with the motion of the axis, also has implications on measurement uncertainty. Of the commercially available metrology tools used in this study, only the laser displacement measurements presented challenges during setup. In a typical setup on a machine tool, where one motion axis can usually be used to aid in alignment, it is relatively easy to align the laser with the return beam within 1 mm , resulting in an expanded uncertainty due to misalignment of less than $1\text{ }\mu\text{m}$. Because the laser head is relatively large compared to the AM build chamber, it was necessary to place the laser outside the machine and to use a turning mirror to align the beam to the axis being tested. The lack of a motion axis orthogonal to the measurement axes (aligned to the laser head) made the initial alignment of the laser beam more difficult. This is simply overcome by the addition of linear and rotary stages to the optical fixturing, allowing for small adjustments of the optics. However, with this method it is often more convenient to accept alignment when the return beam has sufficient intensity, rather than estimating the actual alignment error. In this case, alignment error is

assumed to be on the order of 2 mm , increasing the expanded uncertainty due to misalignment to approximately $6\text{ }\mu\text{m}$.

CONCLUSIONS

This study shows that existing machine tool metrology equipment and standards can be effectively applied to LPBF type machines. What is needed is a standards document providing guidance specific to AM machines on which test(s) to perform and the respective conditions. The direct measurement of individual machine errors provides manufacturers and end users with diagnostic information and error models applicable to a wide range of part geometries.

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IN-SITU MONITORING IN ADDITIVE MANUFACTURING USING CONTACT IMAGE SENSORS

David B. Pedersen¹, Eythor R. Eiriksson², Henrik Aanaes² and Hans N. Hansen¹

¹Department of Mechanical Engineering

²Department of Applied Mathematics and Computer Science

Technical University of Denmark

Kgs. Lyngby, Denmark

INTRODUCTION

With the growing acceptance of Additive Manufacturing (AM) as a family of hyper-flexible additive machine tools, it has been an on-going objective of the Technical University of Denmark to implement flexible computer vision based geometrical verification systems for AM machine tools, allowing for automated in-situ 3D metrology [1-4]. These systems allow for automated in-situ 3D metrology. Prior art value this type of automated geometrical verification as an enabling technology that will allow for efficient verification of highly complex components manufactured by the principles of mass-customisation [4]. Earlier implementations of in-situ monitoring systems by the authors have been achieved through CCD camera technology, and allowed for complete geometrical reconstruction of manufactured parts down to 20 μm in accuracy [4].

This paper presents a new and novel method for acquisition of image data in powder-bed based AM machine tools based upon contact image sensors, that has the potential to push resolution and level of integration to new heights. Contact image sensors (or line scan image sensors) are the type of sensor devices commonly found in flatbed scanners. Recent developments have resulted in the readily availability of flatbed scanners with single digit micron resolution [5-6]. The sensor of a state-of-the-art flatbed scanner has an optical resolution of up to 9600 dpi (2.65 μm) [6]. As a result of this, flatbed scanner image sensor technology has recently been used as an enabler for establishing new and effective means for geometrical verification, here amongst the application for three-dimensional analysis of roughness parameters of milled surface by the scanning of samples [7].

With inspiration from these new advances, it is proposed by the authors that by letting a contact image sensor traverse the build chamber with the re-coating unit of a powder-bed based AM

machine tool, an elegant image acquisition system can be integrated into the machine tool. This new and novel method will allow for future integration by machine manufacturers to provide for an unobstructed computer vision system that automatically will scan the surface of the powder bed during the recoating procedure. Single powder grains will from the high resolution of the optical sensor be identifiable on scans, and will not only allow for geometry verification of manufactured components, but allow for ultra-precise per-layer measurements of powder grain size distribution, packing density over the build chamber and defects from the powder consolidation process, all of which can be used for closed-loop control of the machine tool. This paper serves to propose the method, and proof the method by the introduction of a fully functional prototype system, which in its first instalment will be employed for geometry reconstruction from line scan data.

In spirit of the obvious benefits from a manufacturer-integration of the system, focus has been on the realization of a prototype system, that by implementation will not increase the mechanical system complexity and does not affect the manufacturing rate of the AM machine tool onto which the system has been retrofitted. Unlike previous CCD based implementations, lens distortion and ambient light variations are not present in this new system. Image data can be used to verify the manufactured geometry, as done by the authors through Prior Art, and has the potential to generate much higher quality data than what can be achieved through CCD imaging.

METHOD

The prototype system of the proposed contact image sensor based in-situ verification system has been constructed at the Additive Manufacturing research group at the Technical University of Denmark. The system that can be seen in figure. 1 has been retrofitted on a zCorp

310 plus. The zCorp z310 is an older powder-bed system from zCorporation (now 3D Systems) that excel in its simplicity and was thus deemed an obvious candidate for the implementation of the system. The contact image sensor is a 297 mm wide image sensor from a Mustek A3 scanner with an optical resolution of 2400dpi ($11\mu\text{m}$) and with software Interpolated resolution of 9600 dpi ($2.6\mu\text{m}$). The scanner has been set up, so that the sensor will scan the build-chamber as an integrated part of the powder recoating sequence.

The current implementation does not possess an optical scan resolution where individual powder grains can be identified in acquired image data, as can be achieved, since the contact image sensor module had to be sourced with ease-of-integration in mind. Single grain identification is possible through oversampling and interpolation, but has not yet been pursued during the initial proofing of the prototype system.

Proofing and testing the system was done to prove the geometrical reconstruction capabilities of the system, based upon Prior Art [2-4] and carried out by manufacturing a hole plate artefact. From this artefact the robustness of the prototype system is subsequently assessed.

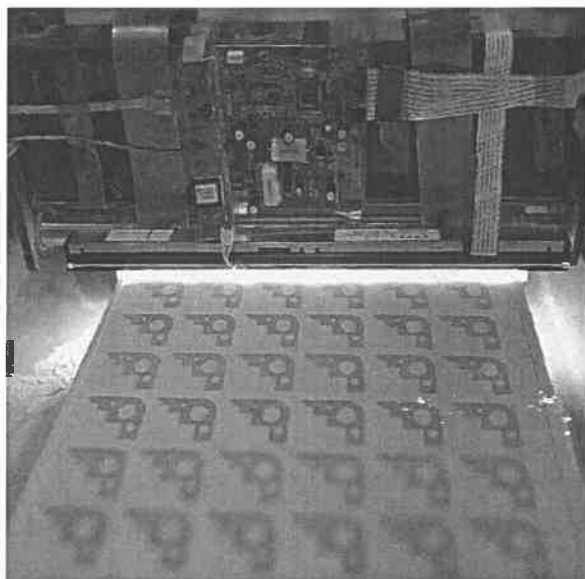


FIGURE 1. Contact Image Sensor based acquisition system on a zCorp z310 plus during a production run.

For each image acquired from the contact image sensor, a sequence of image processing is

carried out. Since the contact image sensor is retrofitted to the z310, the raw image from the contact image sensor will be distorted since it is hitching along with the stock powder recoating unit, and is dependent on the predefined motion pattern for spreading a new layer of powder over the build chamber. Acceleration of the recoating unit decreases sampling density and will compress the scanned image whereas deceleration of the recoating unit increases sampling density and will stretch the scanned image. The effect can be seen in figure 2. The direction of travel of the gantry, and thus the scan direction is from left to right, where on the right hand side, the image has been stretched from the increasing sampling density during deceleration of the gantry system.

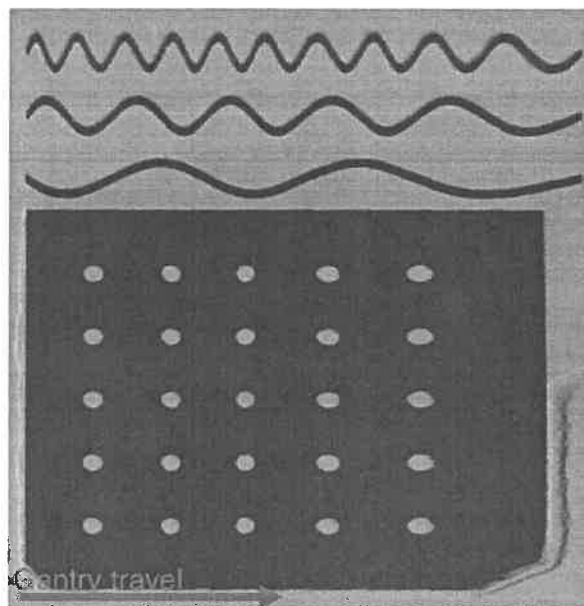


FIGURE 2. Raw and distorted image acquired from the contact image sensor. Top: Sine wave for image correction purposes Bottom: Calibration plate printed to validate the process.

The primary obstacle that was faced from treating image data was to derive the position of the gantry and recoating unit during scanning in order to take the stretching of the image into account. The position cannot be extrapolated from the machine software real-time, and it was optioned not to tap into the machine rotary encoder system. To solve this, it was chosen to use a sinusoidal position reference so that the position of the gantry of the z310 could be accounted for at all times. On a production setup

featuring the proposed in-situ scanning system, this reference is preferably comprised of a stand-alone calibrated waveform imprinted on a straight glass scale.

Spite this, it was decided to manufacture a geometry shaped as a sine wave directly with the z310 as part of the build-job, to be used as a positional encoder. This method relies on the geometrical accuracy of the z310, to validate itself, and can therefore be regarded as being flawed in its implementation. This is done by intent, to distinctly show the robustness of the system. By letting the z310 manufacture its own calibration standard along with each manufactured layer, error constituents from the vision system can be isolated. If a subsequent analysis of a reconstructed geometry shows that any measure deviates from nominal value, this is a direct indication of the variance of acquisition of image data from the contact image sensor system, and thus the reproducibility of the imaging system.

IMAGE PROCESSING & ALGORITHMS

Image processing is comprised of two major steps. The initial is to clean up and apply correction to each image frame captured during a build job. The second step is to reconstruct geometry from each captured image frame, by identifying the holes in the hole plate so that a reconstruction of the manufactured artefact can be obtained. The latter is carried out according to Prior-Art published by the authors [1-4]. Clean up and correction is carried out as follows for each image frame.

Bias removal

In order to remove intensity inhomogeneity from the raw image, a sample of the bias field is taken from the image background. From this a gain calibration matrix is generated from the bias field sample. An element-wise division of the image matrix with the gain calibration matrix is subsequently done to remove the bias field from the image.

Sine extraction

The sine wave is extracted by an element-wise thresholding in order to binarise the waveform matrix. The waveform is gathered from a mean of the thresholded waveform matrix as seen in figure 3. The waveform is finally normalized to amplitude of 1.

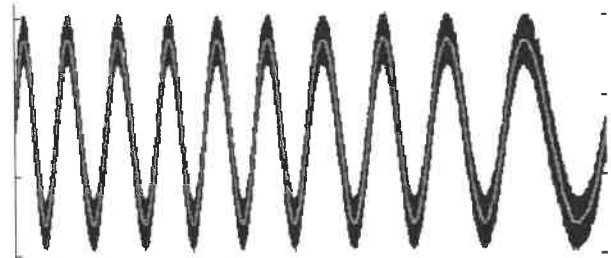


FIGURE 3. Sine wave extraction for extrapolation of contact image sensor position.

Phase extraction and unwrapping

From the sine wave, the phase is extracted using Hilbert transform. The phase angle is calculated from the Hilbert transform, and then unwrapped. The procedure can be seen in figure 4.

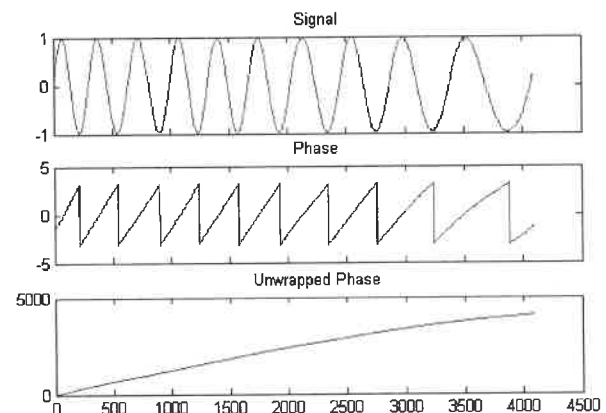


FIGURE 4. Phase extraction and unwrapping of the sine waveform.

Finally the image correction can be applied according to the unwrapped phase in the direction of gantry travel, and data gaps can be interpolated in the image matrix. This is followed by a scaling to match sensor resolution along the gantry to the length of the unwrapped phase vector over the gantry travel distance.

Circle Hough Transform

Finally, in order to validate the quality of the processed image, a circle Hough Transform feature extraction is applied in order to detect the circles on the hole plate artefact. It is a specialization of Hough Transform. The result can be seen in figure 5.

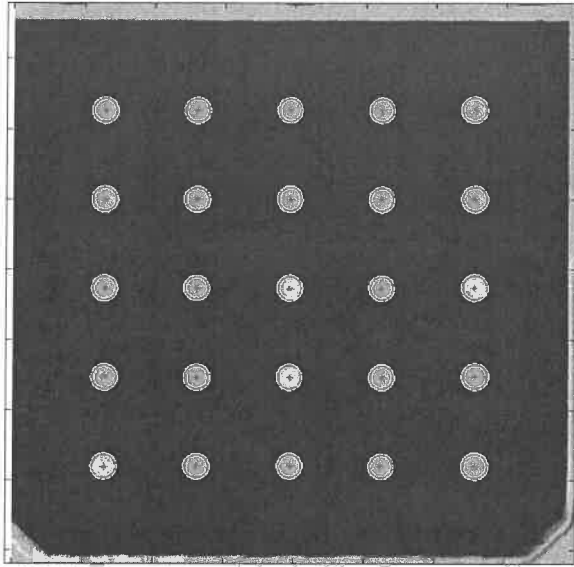


FIGURE 5. Holes detected by the Circle Hough Transform method.

VALIDATION & RESULTS

Since the prototype system manufactures its own sinusoidal reference standard, all measurements are expected to conform to nominal values. Momentarily assuming the absence of measurement uncertainty from the contact image scanning system, and a complete stable AM process, every measured point will theoretically match nominal values of the manufactured artefact. Any divergence from this ideal, is therefore an expression of the decreased robustness to the ideal image acquisition system.

Validation of the method has been carried out from manufacturing the geometrical features previously depicted in figure 2. A series of 6 images was randomly chosen for validation of the method, yielding comparable results. Thus the analysis was continued focusing on one randomly selected image.

For the selected image, upon processing, each hole location detected has been correlated with the corresponding nominal value (shown as a grid) in figure 6. The plot has been magnified by a factor of 10 to clearly visualize errors that would otherwise not be perceived, and a scale bar is present in the upper right hand corner of the plot.

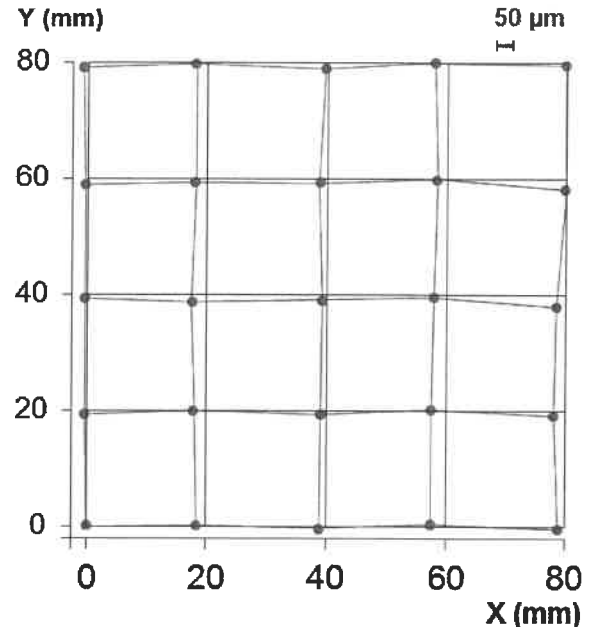


FIGURE 6. Hole positions (blue) as measured by the contact image scanner system referenced to nominal values(grid lines) at 10 X error magnification.

It can be seen that no data point in the plot is further from nominal than $50\mu\text{m}$, and as such the image acquisition system as a whole conform within said range. More noticeably is it that the horizontal error component is larger for all data points, which indicate that better performance can be yielded if the assumptions relating to the quality of the sinusoidal reference and stability of the process not hold true, and an external calibrated sinusoidal reference is used.

CONCLUSIONS & FUTURE WORK

A method and a fully functional prototype system for Contact Image Sensor based in-situ verification of powder-bed based AM machine tools has been demonstrated. The motivation behind this work is manifold. A robust in-situ process monitoring and geometrical validation system is highly advantageous, especially if aiming to meet the visions of increasing enrolment of manufacturing equipment, tailored for mass customization. Furthermore the technology will offer the potential to monitor and control powder bed based AM processes from parameters such as the powder grain size distribution and the corresponding packing within the build chamber. Finally the system is very easily integrated into powder-bed based

systems due to the seamless integration potential with the recoating subsystem, which already traverse the build for each recoating sequence.

The system in its first implementation has shown promising results in its capabilities for acquiring image data in-situ while the machine tool is building objects, layer-by-layer. The system was shown to be in accordance with reference measurements within 50 μ m. A fixed calibrated sine wave ruler will in future retrofitted implementations easily be attached along the build-chamber in order to provide calibrated positional feedback. It is expected that from the current state of development within the contact- and line image sensor technology, and through ASICS/FPGA hardware, it is a matter of implementation to unleash the capability of providing ultra-high resolution scans of the powder bed surface with single digit micron precision, and real-time mapping of the powder, and thus has the potential to be one of the most capable sensor technologies for the powder-bed AM machine tool of tomorrow.

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In Situ Surface Metrology of Laser Powder Bed Fusion Processes Using Fringe Projection

Bin Zhang¹, John Ziegert², and Angela Davies¹

¹Department of Physics and Optical Science
The University of North Carolina at Charlotte,
Charlotte, NC, USA

²Department of Mechanical Engineering and Engineering Science
The University of North Carolina at Charlotte,
Charlotte, NC, USA

INTRODUCTION

In situ surface metrology to measure geometric accuracy, surface roughness and surface contour hold the promise of enhanced understanding of the process signatures of modern metal additive processes and potential ability to enhance process control on a layer-by-layer basis. State-of-the-art interferometric surface profilers can provide high quality surface measurements, but are unsuitable for in situ measurement applications due to their short working distance. Our previous work has presented a custom-designed fringe projection system for in situ monitoring of the Laser Powder Bed Fusion (LPBF) processes [1], [2]. The preliminary results have shown our fringe projection technique as a viable and inexpensive solution that provides in situ surface topography data to monitor the fusion process and the evolving quality of the part during the build. This paper updates our previous work and demonstrates substantial improvements in lateral and height resolution of the system. The modified system has a lateral point spacing of 6.8 μm and a height measurement repeatability of 0.5 μm .

FRINGE PROJECTION SYSTEM

Hardware Design

The fringe projection sensor consists of a commercial DLP projector (Vivitek Qumi Q5) and a high resolution machine vision camera (Point Grey Flea 3). The measurement system is designed to operate on the LPBF testbed machine chamber, designed by Edison Welding Institute, as shown in FIGURE 1. The projector is mounted on top of the chamber, illuminating the powder bed through an AR coated glass window at about a 35° angle. The original projector lens is replaced by an external lens system, which consists of a 125 mm achromatic doublet lens and an adjustable lens tube. This custom lens

system reduces the projected image to about 45 × 28 mm at an approximately 800 mm working distance. This leads to a projected fringe pitch as small as 0.35 mm/cycle. This small fringe pitch is the key to achieving better height resolution. The machine vision camera is mounted inside the chamber, about 200 mm above the powder bed. The camera has a resolution of 4096 × 2160 pixels and a field of view of around 28 × 15 mm, giving a lateral point spacing of 6.8 μm per pixel.

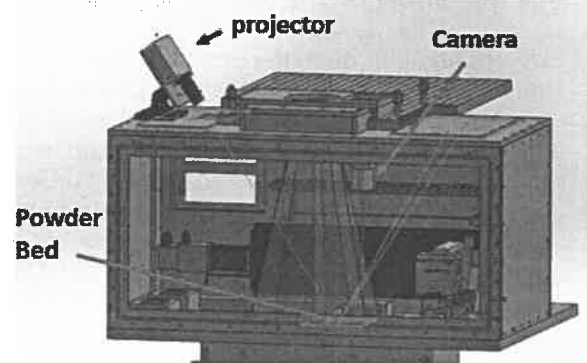


FIGURE 1. Configuration of the fringe projection system on the LPBF machine chamber (some parts are hidden for clear visualization).

Phase Shifting Algorithm

The fringe projection system uses a phase shifting algorithm to measure the height variation of an object [3]. Studies have shown that a phase-shifting pattern codification strategy can achieve better resolution than other strategies such as gray coding, n-ary and spatial neighborhood coding [4]. The fringe patterns of the phase shifting algorithm are sinusoidally modulated gray scale images. The irradiance distribution is written as,

$$I_i(x, y) = I_0 \left[1 + \cos \left(\frac{2\pi x}{p} + \delta_i \right) \right] \quad (1)$$

where i indicates the i^{th} image, I_0 is the irradiance modulation, p is the fringe pitch, and δ is the phase-shifting step size which is given by

$$\delta_i = \frac{i-1}{N} 2\pi, \quad i = 1, \dots, N. \quad (2)$$

where N is the total number of phase steps. A seven-step ($N=7$) phase shifting algorithm is chosen in this study as a balance between the number of required images and the lowest phase error. The wrapped phase map is given by,

$$\phi(x, y) = \arctan \left(\frac{-\sum_{i=1}^N \sin(\delta_i) I_i(x, y)}{\sum_{i=1}^N \cos(\delta_i) I_i(x, y)} \right) \quad (3)$$

In practice, the “ $\arctan$ ” function is usually replaced by the four-quadrant inverse tangent function, $\text{atan2}(Y, X)$, to remove the ambiguity of sign of the numerator and denominator.

After obtaining the wrapped phase map, a phase unwrapping procedure is needed to unfold the wrapped phase, which lies in the range from $-\pi$ to π , to an extended range. A reference-based phase unwrapping algorithm is introduced here to enhance the speed and robustness of the unwrapping. The advantage of this algorithm is that the unwrapping is performed at each pixel location. Thus, any phase unwrapping error will not propagate through the rest of pixel array. The unwrapped phase map of the first powder layer is obtained by using the Itoh phase unwrapping algorithm [5]. The unwrapped phase map is then fit to Legendre polynomials (up to the 3rd order) to remove the surface roughness. The fitted phase map contains only the carrier phase of the projected fringes at a reference height level. The fitted map is later used as the reference map to unwrap the rest of the wrapped phase maps. The unwrapping algorithm can be written as

$$\phi_u(x, y) = \phi_r(x, y) + 2\pi \cdot \text{Round} \left(\frac{\phi_{ref}(x, y) - \phi_r(x, y)}{2\pi} \right) \quad (4)$$

Where ϕ_u is the unwrapped phase map, ϕ_r is the wrapped phase map, ϕ_{ref} is the reference map, and the operator “ Round ” means rounding to an integer number.

Calibration

The conversion from unwrapped phase map to height map in metered space is called “effective wavelength calibration” [6]. The effective wavelength is defined as

$$\lambda_{eff} = \frac{2\pi}{\Delta\phi/\Delta h} \quad (5)$$

where Δh is the height change and $\Delta\phi$ is the corresponding phase change. The effective

wavelength is calibrated by measuring a series of unwrapped phase maps while moving the vertical stage of the LPBF machine over a range from -0.5 mm to 0.5 mm in increments of 0.1 mm. FIGURE 2 shows the calibration result at the center pixel in the calibration region. This plot confirms the linear relation between the phase and height within the small height range. Thus, a straight line is fit to the data using the least square method [7], and the slope of the line is calculated to be 12.24 rad/mm. Using this number in Equation 5 gives the average effective wavelength of 0.516 mm/cycle. Repeating this process for each pixels in the field of view, the effective wavelength can be mapped on a pixel-by-pixel basis. FIGURE 3 shows the effective wavelength map. As shown in this figure, the variation of the effective wavelength is approximately 0.043 mm/cycle.

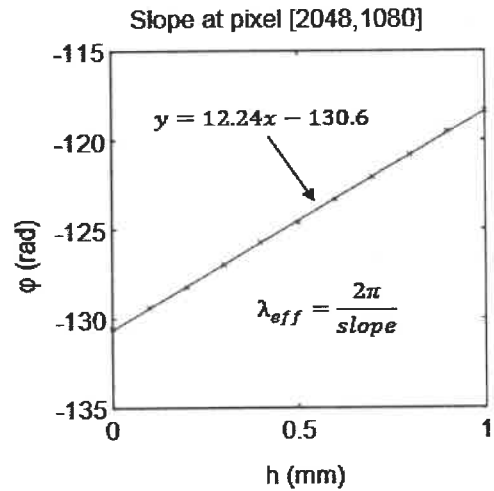


FIGURE 2. Plot of unwrapped phase as a function of height (at the center pixel)

Average $\lambda_{eff} = 0.516$ mm/cycle, PV = 0.043 mm/cycle

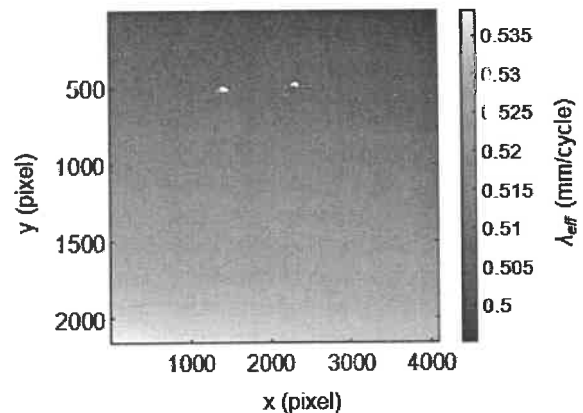


FIGURE 3. Effective wavelength map (color online)

The height map, $z(x,y)$, is written as

$$z(x,y) = \lambda_{eff}(x,y) \cdot \phi(x,y) \quad (6)$$

where $\phi(x,y)$ is the unwrapped phase map after subtraction of the reference map (Equation 4).

The lateral conversion from pixel location to X, Y position in millimeters is achieved by imaging a calibrated grid artifact. The grid artifact contains an array of externally calibrated dots with an average spacing of 6.5 mm. This artifact is placed on the build platform at the reference height level (where the reference map is obtained), and the image of the grid is captured. The average grid spacing in the image is counted to be about 956 pixels. Thus, the lateral conversion factor from pixels to millimeters is 0.0068 mm/pixel. This conversion is straightforward because the machine-vision camera is looking perpendicular to the powder bed. The more general situation where the camera is looking at an arbitrary angle requires a perspective correction procedure. This procedure can be found in our previous paper [2].

EXPERIMENTS AND RESULTS

Experiments are conducted on the LPBF machine shown in FIGURE 1. The nominal process parameters for this machine are the following: laser power = 290 W, scan speed = 960 mm/s, hatch distance = 0.09 mm, and powder layer thickness = 40 μm . To test the performance of the developed fringe projection technique, three 6 $\times$ 6 mm square pillars are created with various laser powers to see if different “process signatures” can be detected. The field of view of the measurements is about 28 $\times$ 15 mm with a lateral point spacing of 6.8 μm . Measurements are taken before and after fusion on each powder layer.

In situ Topographies

FIGURE 4 shows the projected fringes on a fresh powder layer. The average fringe pitch is 0.35 mm/cycle. The small fringe pitch allows measurement of height variations as small as 1/1000 effective wavelength, about 0.5 μm . Measurements of a fused surface with a confocal microscope have shown the height variation to be on the order of tens of micrometers. Thus, no distinct fringe deformation is observed in the photograph, but the height map of this surface, as shown in FIGURE 5, shows clear texture. The waviness in the y direction has a height variation around 50 μm and a wavelength around 0.8 mm. This is likely due to vertical oscillatory motion of recoating arm as it spreads the powder layer. As

can be seen from FIGURE 5, there are some white points around the boundaries of the fused squares. They correspond to the bright points in FIGURE 4, where the boundaries of the fused squares are not fully covered with powder. Camera saturation caused by the highly reflective metal surface leads to no meaningful data at those white points, and is a common challenge to all optical profilers. To decrease the percentage of data drop outs, a dynamic range enhancement technique can be implemented [8]. The percentage of data drop-out in FIGURE 5 is ~1%, and can potentially provide useful information about the uncovered metal surface.

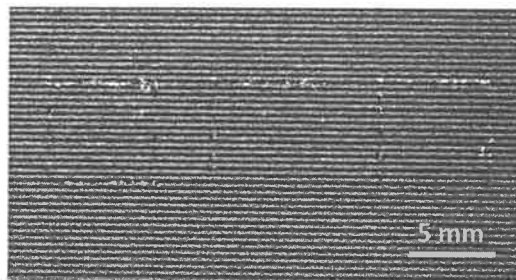


FIGURE 4. Photograph of deformed fringe pattern on a fresh powder layer (at the 2nd layer). Three squares are fused beneath.

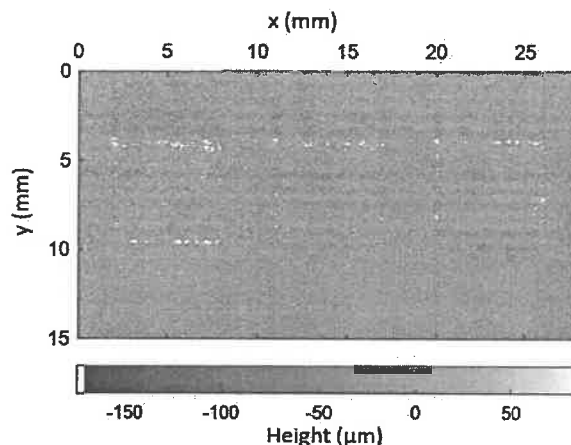


FIGURE 5. Height map of the fresh powder layer in FIGURE 4. White points are data drop outs due to camera saturation. (Color online)

FIGURE 6 shows the deformed fringe pattern on the same layer after fusion. The three squares are fused with laser powers of 350 W, 290 W and 230 W (from left to right). No significant differences are seen in the photographic images, although the fringes on the fused metal surfaces clearly have lower visibility than those on the powder surface. The height map of the fused powder layer is shown in FIGURE 7. There are subtle differences between the fused surfaces on

the three squares. For example, the edges of the left square is more raised than the others, and all the fused squares have different surface texture. Although they were fused with different laser powers, the three squares share several common "signatures". Firstly, the boundaries of the fused squares are all surrounded by narrow grooves. Secondly, the edges of the fused squares are slightly raised compared to the center. Thirdly, the average height of the fused squares is lower than that of the powder surface. This can be observed as the color change between the fused surface and the unfused surface. Lastly, the splattering drops created by the laser fusion are seen as the bright yellow dots on the map.

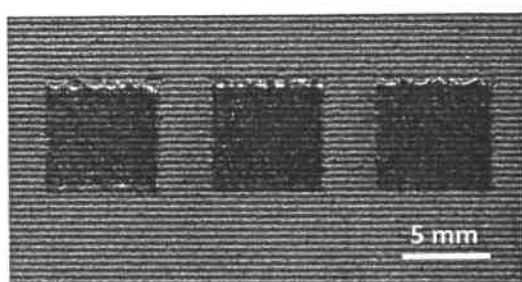


FIGURE 6. Photograph of the deformed fringe pattern on the powder bed after laser fusion (at the 2nd layer). Three squares are fused with laser power 350 W (left), 290 W (middle) and 230 W (right) respectively.

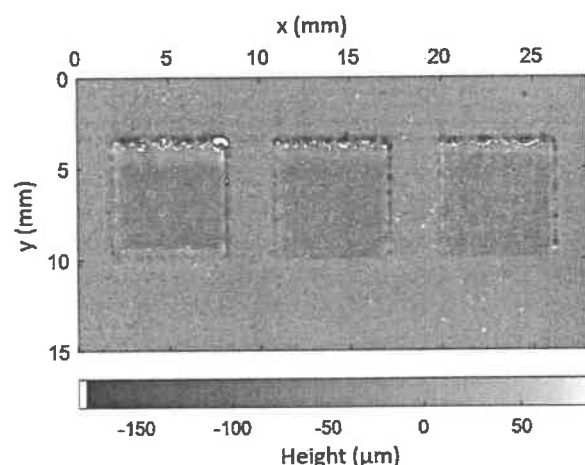


FIGURE 7. Height map of the fused powder layer in FIGURE 6. White points are data drop outs due to saturation. (Color online)

Monitoring the Layers

To demonstrate the information available from the layer-wise measurement procedure, the left square is cropped from each height map. FIGURE 8 shows the 3D height maps measured at Layer 2, 4, 6 and 8. The white points caused

by camera saturation are replaced by interpolated points based on a nearest-neighbor algorithm. The left column shows the height maps of the fresh powder layers. Each powder layer presents a different surface texture. For example, the second layer of powder shows more surface waviness compared to the others.

The right column of FIGURE 8 shows the fused metal surfaces. One observable trend is the edges of the square become smoother and flatter as the build layers accumulate, which possibly indicates an evolution of the process to a steady-state condition. The laser raster is along y direction, and a subtle linear texture in this direction begins to appear beyond the first few layers. There are also some features that remain largely unchanged as the layer number increases, including the narrow grooves around the boundaries, the average height of the fused surface below the powder level, abrupt changes in the elevation at the edges of the fused region, and the height variation within the fused region. The splattering drops show up as bright yellow dots in the maps, both inside and outside the fused region.

Zoomed View

To fully take advantage of the lateral resolution, a 1×1 mm patch is cropped from the center of the fused surface as shown in FIGURE 9. The peak-to-valley height variation in this map is around 120 μm . The laser raster direction is along the y-axis, and the laser spot diameter is about 100 μm . Given the significant surface roughness, the weld line texture is not clear in this region at this magnification.

FIGURE 10 shows a 1×1 mm patch of the height map containing the bottom right corner of the left square. It has been reported that a small metal ball can form at the corner of the fused surface if heat dissipation is insufficient [9]–[11]. The height map shows an elevated corner about 70 μm above the powder surface, consistent with this claim. Another observation is the three raised "line" structures on the corner. The direction of the line structure is parallel to the laser scan direction. Each line is about 200 μm wide and 30 μm high.

SUMMARY

This paper demonstrates an in situ layer-wised surface topography metrology system suitable for integration with the LPBF additive process using a fringe projection technique. This in situ sensor

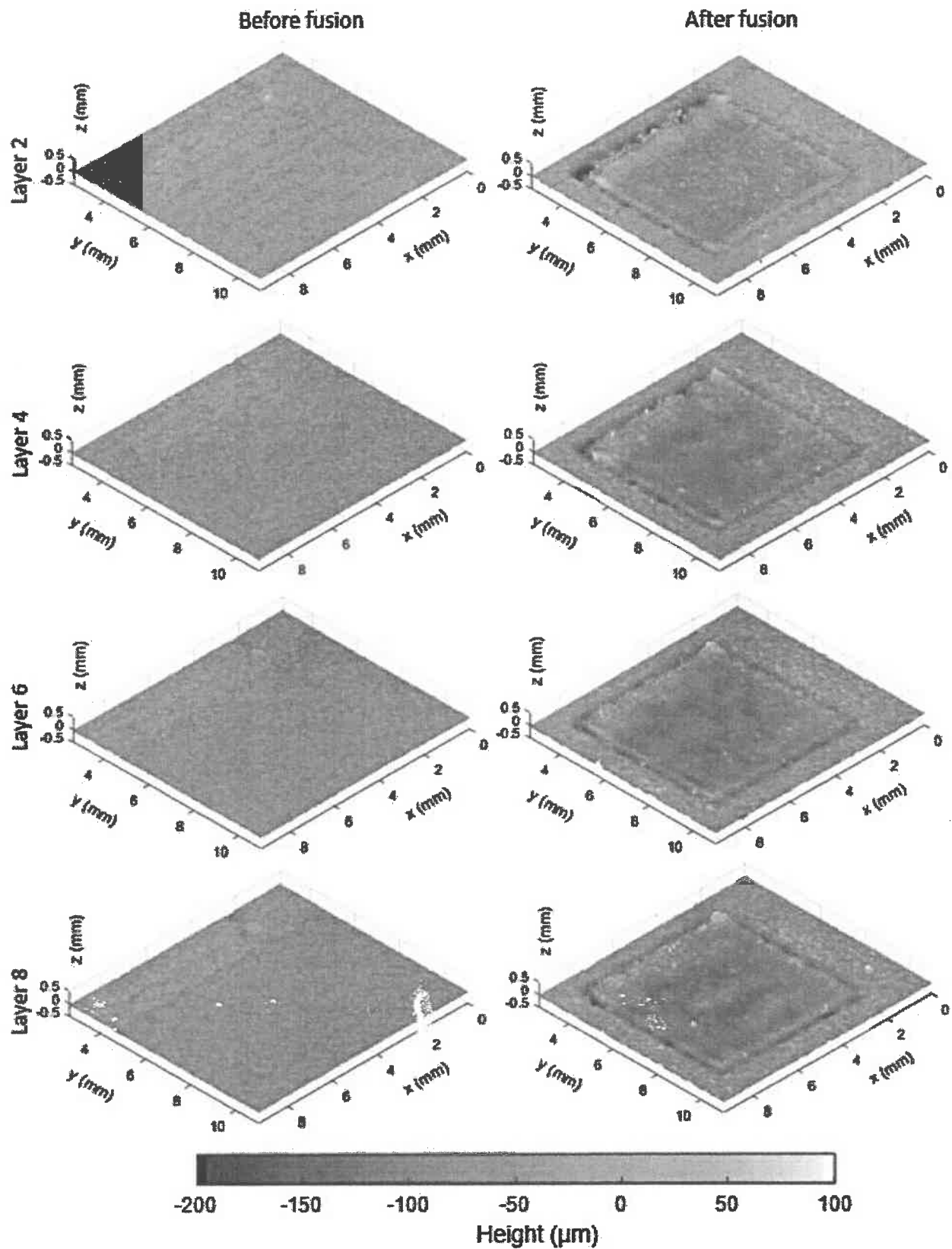


FIGURE 8. Local topographies around the left square before and after laser fusion measured on every other layer. (Color online)

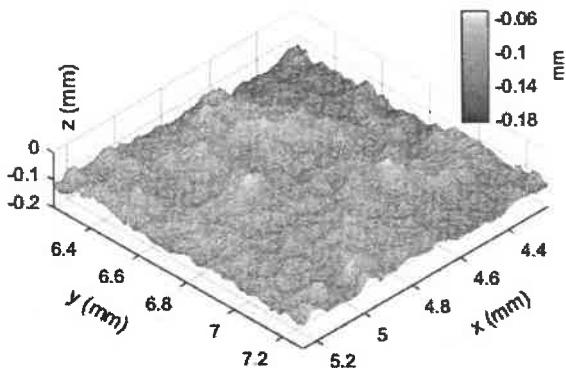


FIGURE 9. Local topography at the center of the fused square at the 18th layer. (Color online)

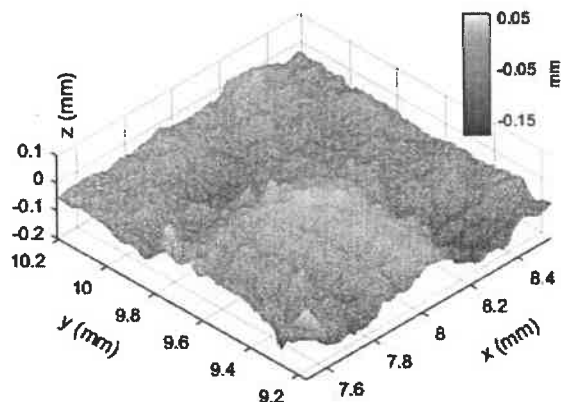


FIGURE 10. Local topography at the bottom left corner of the fused square at the 18th layer. (Color online)

can measure the surface topography of the powder layer before and after laser fusion. To maximize the resolution, the projector and camera are adjusted to image a 28×15 mm field of view with a point spacing of $6.8 \mu\text{m}$. Larger fields of view can be achieved by implementing standard pan and zoom technology. The height measurement repeatability is about $0.5 \mu\text{m}$. This study has demonstrated the ability to measure the metal/powder surface height variation following fusion of each layer. These data are expressed relative to a fixed reference coordinate system through the entire build process. These measurements offer the potential for benefits in process optimization and control, and the analysis and characterization of the build area, including determining boundaries of the fused region, measuring the height variation of the fused surface, and tracking the vertical motion of the build platform.

ACKNOWLEDGEMENT

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In-Situ Temperature Measurement During the Electron Beam Melting Process of Inconel

R. B. Dinwiddie, M. M. Kirka, R. R. Dehoff, L. E. Lowe, G. S. Marlow
Oak Ridge National Laboratory, Manufacturing Demonstration Facility, 2370 Cherahala Blvd.,
Knoxville TN 37932-1563

ABSTRACT

The Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL) provides world-leading capabilities in advanced manufacturing (AM) facilities which leverage previous, on-going government investments in materials science research and characterization. This facility contains systems for producing components with complex geometries using AM techniques (e.g. 3D-Printing). Various metal alloy printers, for example, use an electron beam melting (EBM) system for creating these components which are otherwise extremely difficult, if not impossible, to machine. ORNL has partnered with manufacturers to assist in improving the final part quality of a component and to develop new materials for use in these devices. One method currently being used to study the (AM) processes relies on the advanced imaging capabilities at ORNL. High performance midwave IR cameras are used for in-situ process monitoring and temperature measurements. This paper discusses the trends in temperature of the EBM of an Inconel 718 powder bed and melted regions as a function of layer number, relative position and time. These data are important for the development and verification of e-beam additive manufacturing models. Ultimately, these imaging systems have the potential for routine use for online quality assurance and feedback control.

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Keywords: Additive Manufacturing, e-beam melting, Inconel, IR imaging, in-situ temperature measurement

QUALITY CONTROL BY ARTIFICIAL VISION OF ADDITIVELY MANUFACTURED OBJECTS IN THE ARCAM Q10 ELECTRON BEAM MELTING PROCESS

Vincent Paquit¹, Ryan R. Dehoff¹, Michael M. Kirka¹

**¹Manufacturing Demonstration Facility
Oak Ridge National Laboratory
Knoxville, Tennessee, USA**

ABSTRACT

Electron Beam Melting Process The Manufacturing Demonstration Facility (MDF) at the Oak Ridge National Laboratory (ORNL) is conducting extensive data analytics research on in situ - monitoring of metal printing processes. We are interested in quantifying, monitoring and understanding the strong correlation between printed layers quality and the inerrant printing process parameters are essentials to control additive manufacturing techniques. Ultimately, we aim to conduct inline process monitoring, alteration, and correction using real time sensing and data processing techniques. To this end, we are actively developing image processing techniques coupled to machine learning techniques allowing (1) to detect the presence of porosity and defects, (2) to map geometric inaccuracies and surface roughness, (3) to compare CAD models and printed objects for significant variations, and (4) to perform real time quality control of the parts for validation. This presentation will provide some of the advances and results we have accomplished to date.

Effect of the Surface Finish on the Corrosion Resistance of Direct Metal Laser Sintered Ti6Al4V

Yangzi Xu, Yuan Lu, Christopher A. Brown, Richard D. Sisson, Jr.

Department of Mechanical Engineering

Worcester Polytechnic Institute

100 Institute Road

Worcester, MA 01609, USA

OBJECTIVE

The additively manufactured Ti6Al4V alloy has different microstructure, which leads to varied mechanical properties and corrosion behavior compared to the commercial wrought Ti6Al4V alloys. In terms of the orthopedic applications for Ti6Al4V alloys, surface finish will have significant effect on the corrosion behavior. The goal of this work is to study the influence of various surface finishes on the corrosion resistance of direct metal laser sintered specimens and comparison with commercial alloys.

INTRODUCTION

The as-fabricated and heat-treated specimens were treated by various surface finishes: mechanical grinding (MG) with #1200 sand paper, mechanical polishing (MP) with alumina paste and vibropolishing (VP) with colloidal silica suspension. Surface morphology and surface roughness were analyzed using Olympus laser microscope with MountainsMap® Premium 7.1 software. Phase identification and residual stress were examined by X-ray diffraction. Corrosion resistance of commercial Ti6Al4V specimen was also studied. It was found that specimens treated with vibropolishing, having lower surface roughness (S_a value), possesses higher corrosion resistance. The effect of microstructure, surface roughness and residual stress on the corrosion rate was analyzed quantitatively.

MATERIALS AND METHODS

The Ti6Al4V specimens were fabricated by E-manufacturing solutions Inc. (Krailling, Germany) via direct metal laser sintering (DMLS). Half of the as-fabricated samples were heat treated in a vacuum furnace under 799°C for 4 hours, and followed by air-cooling. The commercial Ti6Al4V (Grade 5) specimens were purchased from McMASTER-

CARR Inc. (Robbinsville, NJ). The as-fabricated, heat-treated and commercial specimens were prepared by various surface finishes: mechanical grinding (MG) using #1200 silicon carbide paper, mechanical polishing (MP) up to 0.05 μm alumina paste and vibropolishing (VP) with 0.05 μm colloidal silica suspension.

Surface morphology tests were performed on an Olympus 3D laser microscope OLS LEXT 4100 with 100x objective. The examined area was 130 μm $\times$ 130 μm . The MountainsMap® Premium 7.1 software was used to analyze the generated three-dimensional images. For a specific specimen, six independent measurements were conducted on the surface, and the average 3D surface roughness values were calculated. The hybrid parameters (S_{dq} and S_{dr}) were also generated from the software. Sfrax was used to conduct area scale analysis of the generated surfaces.

JEOL JSM-7000F scanning electron microscope (SEM) and PANalytical Empyrean 2 X-ray diffractometer (XRD) were used to examine the microstructure and phase identification of the investigated specimens, respectively. The residual stress values were also measured by XRD. The electrochemical tests were conducted in a three-electrode cell with Ag/AgCl (3M NaCl) as the reference electrode, a Platinum wire (surface area: 3.6 cm^2) as the counter electrode and the tested Ti6Al4V specimen as the working electrode in naturally aerated Ringer's solution (6.5 g/l NaCl, 0.14 g/l KCl, 0.12g/l CaCl_2 , 0.2g/l NaCO_3 and 0.4g/l glucose) at 37 °C.

MICROSTRUCTURE AND PHASE ANALYSIS

Microstructure of the as-fabricated, heat-treated and commercial Ti6Al4V specimens are shown in Figure 1. XRD patterns of the corresponding specimens are plotted in Figure 2. In Figure 1(a) of the as-fabricated specimen, predominantly α' martensite

microstructure can be observed due to the fast cooling rate after sintering process. The fine martensite phase results to increased microindentation hardness and reduced ductility in the as-fabricated Ti6Al4V specimens [1]. After post-annealing treatment at 799°C for 4h, coarsening of α' lath can be observed in Figure 1(b). Figure 1(c) shows the equiaxed $\alpha+\beta$ two phase microstructure of the commercial Ti6Al4V specimen, which generally exhibits superior mechanical properties (higher ultimate tensile strength and ductility) [2]. In Figure 2, the XRD pattern of heat-treated specimen shows the developing of β phase at 2θ equals 38.5° which refers to β (011). The XRD pattern of commercial specimen possesses higher amount of equilibrium β phase.

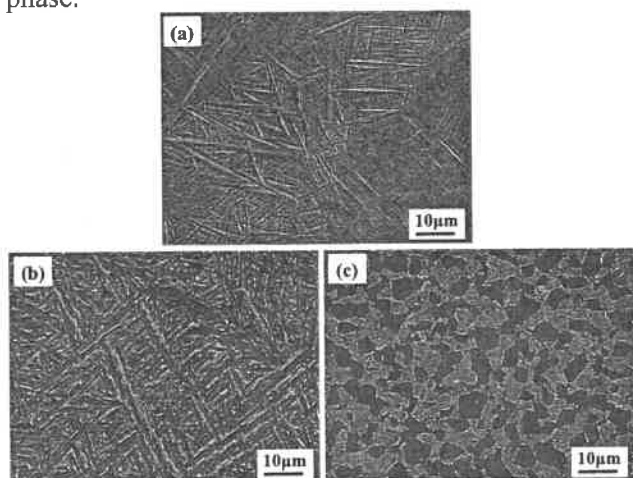


Figure 1: Microstructure of (a) as-fabricated, (b) heat-treated and (c) commercial Ti6Al4V specimens.

SURFACE MORPHOLOGY AND SURFACE PROPERTIES

Various surface finishes were applied on the as-fabricated, heat-treated and commercial Ti6Al4V specimens. The topography images of the as-fabricated specimen under different surface finishes are shown in Figure 3. Due to the manufacturing process of direct metal laser sintering, defects of pre-alloyed powder particles or improper sintering may lead to internal pores of the as-fabricated parts [1]. As shown in Figure 3, some micro-pores and unidirectional scratches can be observed in mechanically ground (MG) specimen. Based on the color scale bar, depth of the scratches was approximately 0.3µm. During mechanical polishing, the applied force may lead to unbinding of some improper sintered powder particles that loosely bonded to the matrix, so the pores are more obvious

after mechanical polishing. In Figure 3, the blue dots in the topography image of mechanically polished (MP) specimen indicate the internal pores with depth of approximately 0.3 to 0.5µm. The vibropolished (VP) surface was smooth and lack of significant pores (VP in Figure 3), because the applied force was lower than MP. Due to the light etching effect of colloidal silicon suspension, the acicular lath can be observed in the vibropolished surface.

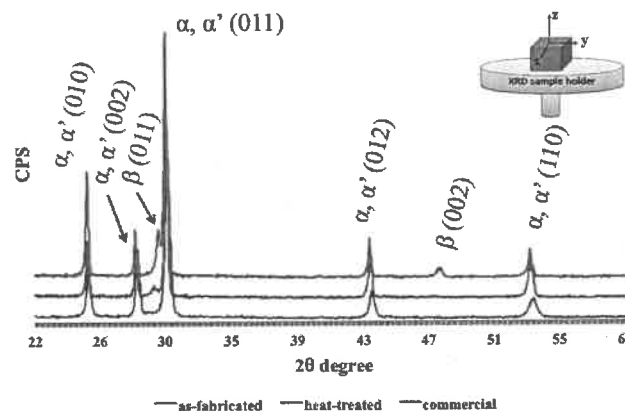


Figure 2: XRD patterns of the (a) as-fabricated, (b) heat-treated and (c) commercial Ti6Al4V specimens. Inset shows how the residual stress values were measured. The designated x, y directions are on the sample surface, and z direction is perpendicular to the sample surface.

Based on the MountainsMap® Premium 7.1 software, the 3D average surface roughness (S_a values) of the specimens with different surface finishes are listed in Table 1. The S_a values increase in the order: VP < MP < MG for all of the investigated specimens, which indicate that MG samples have the highest surface roughness with the S_a values of around 90nm. In accordance with the surface morphology images shown in Figure 3, vibropolishing with lower applied force can achieve a surface with lower S_a values (in the range of 4 to 6.5 nm) than mechanical polishing (in the range of 40 to 55nm) for the as-fabricated, heat-treated and commercial Ti6Al4V specimens.

Apart from the two-dimensional surface roughness (S_a value) parameter, the 3D hybrid parameters were studied to analyze the surface morphologies. The resulting hybrid parameters (S_{dq} and S_{dr}) are also listed in Table 1. The root mean square gradient (S_{dq}), is the RMS-value of the surface slope within the sampling area, and the surfaces area ratio (S_{dr}) expresses the increment of the interfacial surface

area relative to the area of the projected plane
[3][4][5].

Specimen	S _a (nm)		Sdq (deg)	Sdr (%)	Corrosion rate (μm/year)	Residual stress (MPa)	
	Mean values	Standard deviation				x	y
as-fabricated - MG	91.0	4.4	0.49	6.49	0.307	-56.4 (12.3)	+47.0 (12.3)
as-fabricated - MP	52.7	8.8	0.083	0.29	0.176	-100.3 (15.7)	+91.2 (15.7)
as-fabricated - VP	4.7	0.8	0.0176	0.0154	0.136	-19.6 (12.1)	+155.8 (12.1)
heat-treated - MG	89.8	9.5	0.544	8.29	0.267	-73.9 (9.0)	-92.7 (9.0)
heat-treated - MP	55.2	13.3	0.095	0.24	0.067	-96.7 (6.3)	-100.0 (6.3)
heat-treated - VP	6.4	1.7	0.0193	0.0185	0.048	-62.8 (8.8)	-107.8 (8.8)
commercial - MG	82.6	7.1	0.442	6.19	1.105	-43.3 (8.4)	-44.2 (8.4)
commercial - MP	42.8	5.6	0.0913	0.316	0.399	-60.6 (9.1)	-65.8 (9.1)
commercial - VP	5.0	0.9	0.0296	0.033	0.305	-41.9 (5.1)	-25.4 (5.1)

Table 1: Surface roughness (S_a values), hybrid parameters (3D surface parameters: Sdq and Sdr), corrosion rate and residual stress results of DMLS (as-fabricated and heat-treated) and commercial Ti6Al4V specimens.

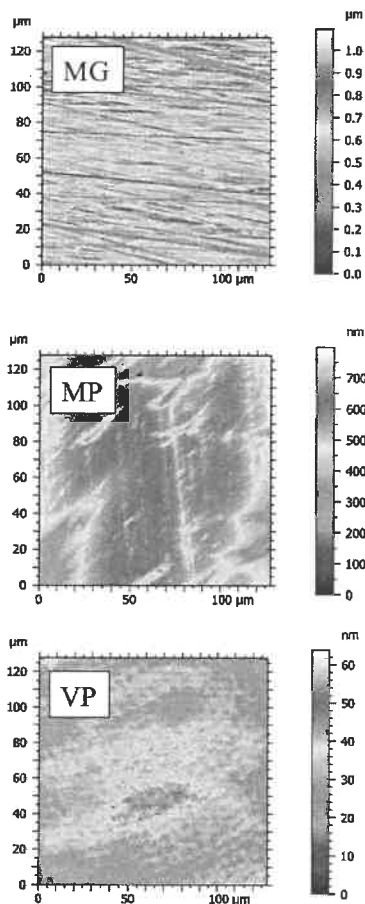


Figure 3: Topography images (under 100x) of the as-fabricated Ti6Al4V specimens under various surface finishes. Palette on the right hand side indicates scale for the corresponding topography image. MG: mechanical grinding, MP: mechanical polishing, and VP: vibropolishing.

As shown in Table 1, the as-fabricated and heat-treated specimens possess higher Sdq and Sdr values than the commercial specimen. The results of hybrid parameters indicate that as-fabricated and heat-treated specimens possess a finer and more intricate texture.

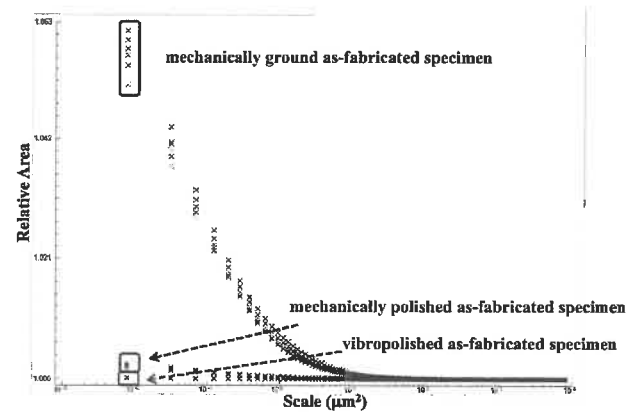


Figure 4: Area scale plots of as-fabricated Ti6Al4V specimens under various surface finishes: mechanical grinding, mechanical polishing and vibropolishing.

The area scale of as-fabricated Ti6Al4V specimens under various surface finishes (mechanical grinding, mechanical polishing and vibropolishing) are plotted in Figure 4. It is obvious that mechanically ground specimens have the highest relative area compared to mechanically polished and vibropolished specimens. For all the six measurements in each condition, MG and MP specimens have some variation in relative area (in Figure 4) due to the

non-uniform distribution of the valleys on the sample surface. As shown in Figure 3, MG specimen possesses peaks and valleys in different depth, MP specimen possesses pores at different locations. Whereas, no significant texture can be observed in the vibropolished specimen, apart from light microstructure due to the etching effect of colloidal Si suspension.

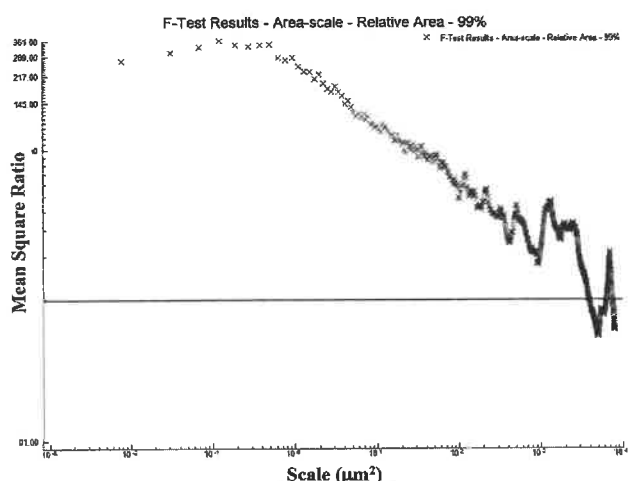


Figure 5: F-test results of area scale - relative area for as-fabricated Ti6Al4V specimens under mechanical polishing and vibropolishing.

The F-test results of area scale - relative area and complexity for as-fabricated Ti6Al4V specimens under mechanical polishing and vibropolishing is shown in Figure 5 and 6, respectively.

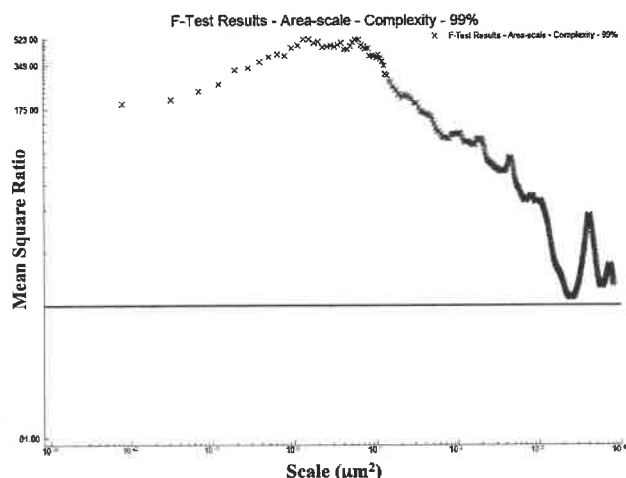


Figure 6: F-test results of area scale - complexity for as-fabricated Ti6Al4V specimens under mechanical polishing and vibropolishing.

Linear regression of correlation between corrosion rate and relative area for the DMLS (as-fabricated and heat-treated) and commercial Ti6Al4V specimens under different surface finishes is shown in Figure 7. Correlation results (R^2 values) between surface roughness (S_a values) and hybrid parameters (S_{dq} and S_{dr}) of DMLS (as-fabricated and heat-treated) and commercial Ti6Al4V specimens are listed in Table 2.

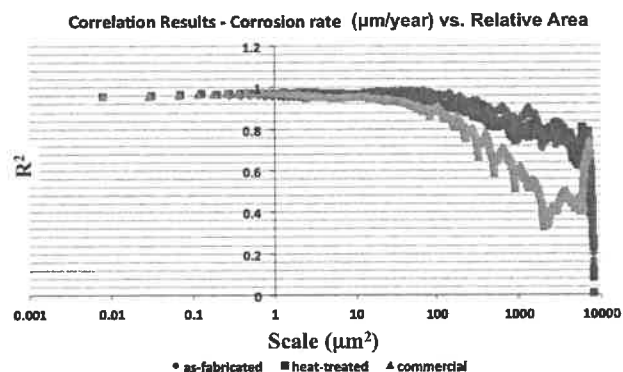


Figure 7: Linear regression of correlation between corrosion rate and relative area for the DMLS (as-fabricated and heat-treated) and commercial Ti6Al4V specimens under different surface finishes.

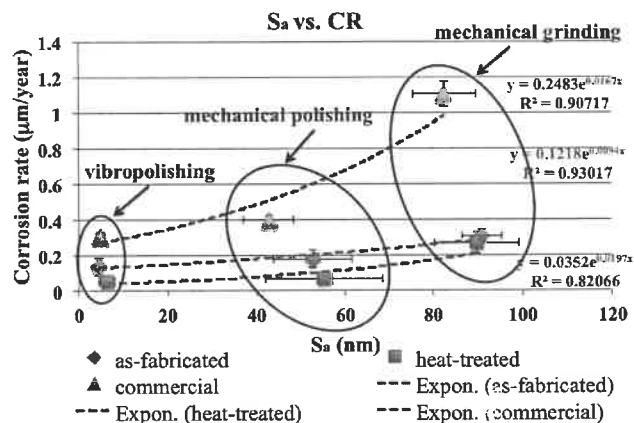


Figure 8: Correlation between 3D surface roughness (S_a values) with corrosion rate of DMLS (as-fabricated and heat-treated) and commercial wrought specimens. The applied three different surface finishes are pointed out.

(1) The difference in corrosion rate between DMLS (as-fabricated and heat-treated) and commercial Ti6Al4V specimens are related to their different microstructure. It was known that the acicular microstructure can easily form compact oxidation

film than two-phase ($\alpha + \beta$) microstructure due to less partitioning effect. As shown in Figure 1, as-fabricated Ti6Al4V specimen possesses acicular α' lath, which get coarsened after heat treatment. So, DMLS specimens possess lower corrosion rate than commercial ones benefits from the more compact protective layer (mainly TiO_2) on the surface [6].

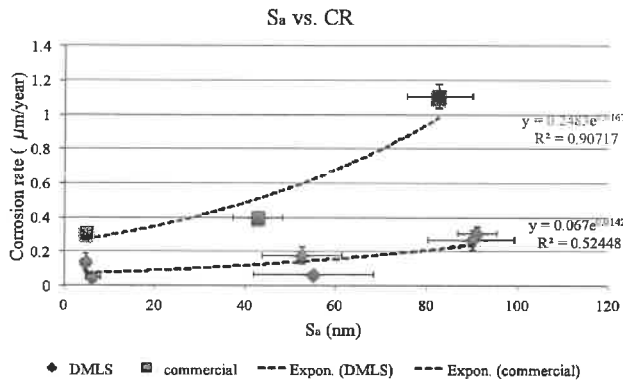


Figure 9: Correlation between 3D surface roughness (S_a values) with corrosion rate of DMLS and commercial wrought specimens.

(2) As shown in Figure 8, the relationship between S_a values and corrosion rate can be quantitatively expressed using exponential fittings. It was generally accepted that higher surface roughness results in lower corrosion resistant, because crevices on the surface would be oxygen depleted region and form galvanic couple with the oxygen rich area [7][8]. After mechanical grinding, scratches lead to gaps with depth of approximately $0.5 \mu\text{m}$, in which oxygen depleted region formed and made MG specimens more vulnerable to corrosion. Based on the exponential fittings, the effect of surface roughness (S_a values) is more significant in two-phase ($\alpha + \beta$) microstructure.

R^2		Sdq (deg)	Sdr (%)	CR (μm)
as-fabricated	S_a (nm)	0.9312	0.9273	0.9302
	Sdq (deg)	/	0.9832	0.9449
	Sdr (%)	/	/	0.9169
heat-treated	S_a (nm)	0.7889	0.7914	0.8207
	Sdq (deg)	/	0.9984	0.9735
	Sdr (%)	/	/	0.9689
commercial	S_a (nm)	0.8882	0.8934	0.9072
	Sdq (deg)	/	0.9117	0.9982
	Sdr (%)	/	/	0.9746

Table 2: Correlation results (R^2 values) between

surface roughness (S_a values) and hybrid parameters (Sdq and Sdr) of DMLS (as-fabricated and heat-treated) and commercial Ti6Al4V specimens.

(3) Between the DMLS specimens with same acicular microstructure, the heat-treated specimens always have lower CR than the as-fabricated ones as shown in Figure 8. Therefore, apart from the effects of microstructure and surface roughness, relieving of residual stress during annealing treatment may be the reason for enhanced corrosion resistance [9]. The residual stress values of the investigated samples are listed in Table 1. As-fabricated specimens have both compressive and tensile residual stress, whereas, annealed specimens possess only compressive residual stress. It was a well-known fact that net tensile residual stress can induce stress-corrosion cracking in Ti alloys at severe environment with the presence of substantial hydrogen contents [10]. In simulated physical fluid with pH of 6.5, the presence of tensile residual stress may be the reason for the inferior corrosion resistance in the as-fabricated DMLS Ti6Al4V. As shown in Figure 9, surface roughness of DMLS (as-fabricated and heat-treated) specimens are correlated together with corrosion rate, but the correlation is not relevant. This may due to the difference in residual stress type of the two samples. Therefore, the corrosion rate maybe affected by the residual stress type but not so relevant to the absolute values of residual stress.

CONCLUSIONS

The effects of various surface finishes on the corrosion behavior of DMLS Ti6Al4V were examined. The 3D surface roughness (S_a values) and 3D hybrid parameters (Sdq and Sdr) increase in the order: VP < MP < MG for all of the investigated specimens, which indicates that MG samples have the highest surface roughness, and VP specimens have less finer and intricate surfaces. The polarization results indicate calculated corrosion rate decreased in the order: MG > MP > VP in all the investigated specimens. Affected by the microstructure, enhanced corrosion resistant was obtained in DMLS (as-fabricated and heat-treated) specimens with acicular microstructure, and inferior corrosion resistant in two-phase ($\alpha + \beta$) commercial wrought ones. Surface roughness (S_a values) affect corrosion rate exponentially, and residual stress type also plays important role especially in DMLS specimens.

ACKNOWLEDGEMENT

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THE EFFECT OF LASER SCAN STRATEGY ON DISTORTION AND RESIDUAL STRESSES OF ARCHES MADE WITH SELECTIVE LASER MELTING

Stacey D. Bagg¹, Lindsay M. Sochalski-Kolbus², and Jeffrey R. Bunn²

¹Metal Joining and Processes
NASA Marshall Space Flight Center
Huntsville, AL, USA

²Chemical and Engineering Materials Division
Oak Ridge National Laboratory
Oak Ridge, TN, USA

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INTRODUCTION

The NASA Marshall Space Flight Center (MSFC) is developing Additive Manufacturing (AM) - both in-space AM for on-demand parts, tools, or structures, and on-earth AM for rapid, reduced-cost, small volume production of complex space-flight hardware. Selective Laser Melting (SLM) is an on-earth AM technology that MSFC is using to build Alloy 718 rocket engine components. An understanding of the SLM-718 material properties is required to design, build, and qualify these components for space flight. Residual stresses are of particular interest for this AM process, since SLM is a series of ~100 μm -wide welds, where highly non-linear heating and cooling, severe thermal gradients and repeated thermal cycling can result in high residual stresses within the component. These stresses may cause degraded material properties, and warp or distort the geometry of the SLM component. The distortions can render the component out-of-tolerance when inspected, and even interrupt or halt the build process if the warped material prevents the SLM machine from operating properly. The component must be scrapped and re-designed, which is time consuming and costly. If residual stresses are better understood, and can be predicted, these effects can be mitigated early in the component's design.

Researchers at the ORNL Neutron Residual Stress Facility (NRSF) have conducted volumetric residual stress measurements on basic shapes of Alloy 718 – through work with

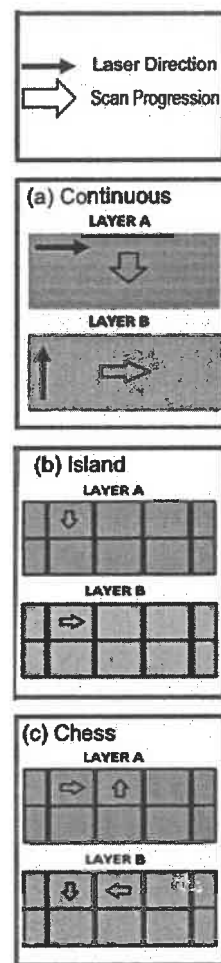


FIGURE 1.
Scanning
Strategies

NASA, Honeywell, the ORNL Manufacturing Demonstration Facility (MDF), and others. This work found that laser-based systems (such as SLM) generate significantly higher residual stresses than electron-beam systems [1], so this is a critical area to address for the SLM technology in particular. This concern is underscored by research that has found residual stresses in excess of 2x the wrought material yield stress in 316L manufactured with SLM [2].

The laser scan and hatching strategy was hypothesized to have an effect on residual stresses, based on the work of Mercelis and Kruth [3] [4]. The common "continuous" scan uses a back-and-forth hatching pattern along the entire dimension of the part in the direction that the laser is scanning. Strategies to reduce residual stresses (proposed by Kruth and his collaborators [3] [4]) segment the layer pattern

into 5 mm x 5 mm squares which are melted in a non-sequential pattern to minimize heat build-up. Concept Laser GmbH, the equipment manufacturer for the SLM

machine used in this research, adopted two versions of this strategy - "chess" and "island," These are shown and described in Fig. 1. This research investigated the effect of these strategies on component deformations and volumetric residual stresses.

BACKGROUND STUDY

An initial study (Bagg, Kolbus and Babu, unpublished) has shown that laser scan strategy has an effect on residual stress, but not in the predicted way – the chess and island strategies designed to minimize stresses actually showed higher stress than continuous scanning in small (20 mm x 10 mm x 6.5 mm) rectangular prism samples. Scanning strategies and component orientations were held identical to the current study, and are described in the Experimental section. Very low stresses were measured in the x-direction for all samples. In the y-direction, compressive stress was seen at the center of the samples. The average stress in the chess pattern was -132 MPa, compared with island at -118 MPa and continuous at -122 MPa. Tensile stress was exhibited in the top layer of the chess sample in the y-direction, which was absent in the other two samples. Tensile stress was seen in the z-direction at the center of the sample for all samples, again with chess averaging the highest magnitude (128 MPa), followed by island (112 MPa) then continuous (97 MPa). Some compressive stress was seen in the z-direction at the corners of the samples on the top layer, with chess netting the highest magnitude. ORNL and NASA continued to expand on this work, and the study described by this extended abstract was conducted to check the results of the previous work and investigate whether this finding applies to more complex components.

The samples in the initial study were cut off the build plate prior to neutron residual stress measurement which relieved stresses that a component would experience during the build. A build interruption approximately half way through the build led to higher stresses near the mid-height of the build rather than the predicted high tensile stresses at the top of the build that have been witnessed in other research [1] [2] [5]. To address these uncertainties, this study investigated the relaxation effect of cutting the components off of the build plate, and was controlled to prevent build interruptions.

An additional feature of this present study was the investigation into build distortions.

Distortions are coupled with residual stresses – if a part has higher stresses, it will deform more if it is not constrained. The hypothesis resulting from the initial study was that the binding between segments did not allow the chess pattern to deform, leading to higher residual stresses – this would also explain why the chess strategy is preferred by machine operators due to it generating less warpage and fewer build interruptions.

EXPERIMENTAL

Sample Preparation

The sample geometry was selected to duplicate a geometry used by Dr. Kruth [3] to investigate residual stresses in SLM through measurement of distortion in an arch. By utilizing an identical sample geometry, results can be compared with Dr. Kruth's. The geometry is shown in Fig. 1.

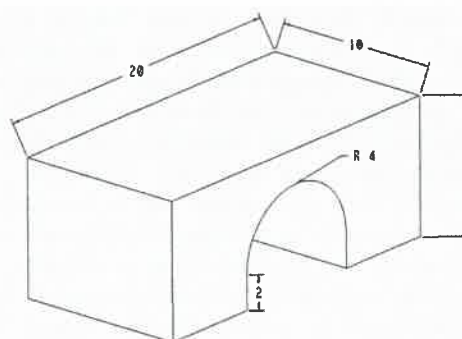


FIGURE 2. Sample Geometry

The SLM process parameters and laser scanning patterns were selected to be identical to the study described in the Background section. These were consistent with parameters used by NASA for printing Alloy 718, shown in Table 1.

Three duplicates of each sample (A, B, and C) were printed on to a 90 mm x 90 mm stainless steel build plate. The Concept Laser SLM scans at +45° and -45° so the samples were oriented at 45° to align the scan hatches with the major axes of the samples, as shown in Fig. 1. After initial surface profilometry measurements, the baseplate was cut into three sections (shown in Fig. 3) and samples were cut off of the two corner sections. All samples were again measured with the profilometer, to investigate distortion from the stresses relieving.

TABLE 1. Sample SLM Parameters

Material	Alloy 718 Powder, 10-45 μm
Layer Thickness	0.030 mm
Laser Power	180 W
Laser Speed	600 mm/s
Hatch Width	0.105 mm
Island Geometry	5 mm x 5 mm squares Overlapping by 0.0225 mm on each side Offset by 1 mm in x and y for each layer
Scan Strategy "A"	Continuous
Scan Strategy "B"	Island
Scan Strategy "C"	Chess

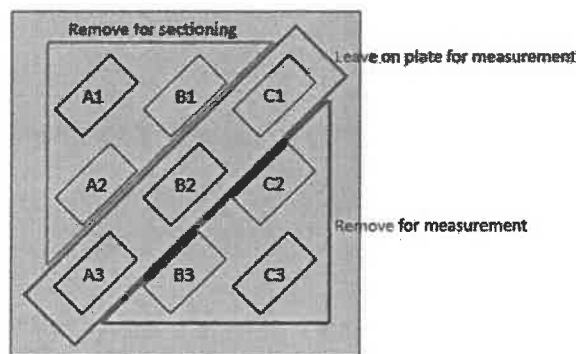


FIGURE 3. Baseplate Configuration

Profilometer Measurements

Non-contact point light profilometry was conducted on the top surface of each component before and after being cut from the build plate. This allowed researchers to characterize the distortion resulting from stress relaxation after the baseplate constraint was eliminated. A Solaris Development Corporation LaserScan was used. This custom profilometer used a Stil CCS Prima chromatic confocal sensor (CCS) paired with a WLC4 optical pen and Optima controller, resulting in a white light CCS which has a 2.5 mm range and 130 nm z-resolution. A 200 mm XY air bearing stage allowed spatial maps to be collected over the surfaces.

Data analysis included leveling over the entire surface using least square plane, and thresholding to remove outlier data where slopes on the rough AM surface exceeded the $\pm 22^\circ$ limit of the CCS. A 3-D plot of the surface was generated for evaluation. A line profile along the

center of each sample was taken from the surface data, and form removal was used to evaluate the curvature of the distorted samples.

Volumetric Residual Stress Measurement

Neutron diffraction at the ORNL High Flux Isotope Reactor (HFIR) NRSF2 was used to measure lattice spacing (d_{hkl}) in the x, y and z planes at the spatially mapped locations shown in Fig. 4 for the purpose of strain calculation. In addition to the experimental samples, lattice spacing on one sectioned sample was measured for a stress-free reference. A gauge volume of 2 mm³ was selected, as it allowed sufficient points for a spatial map while incorporating enough grains for a reliable measurement [6] and assuring gauge volume burial (a partial gauge volume introduces a peak shift that can be mistaken for strain [7], so full gauge volume burial is critical).

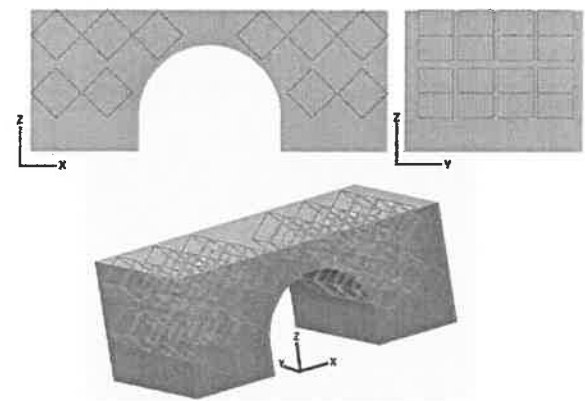


FIGURE 4. Spatially Mapped Gauge Volumes shown in Sample

Residual strain was calculated in the sample x, y and z directions, assuming these to be the principal axes (shear strains are zero). Strain is calculated from the difference in measured inter-planar lattice spacing d_{hkl} from the stress-free reference spacing d_{hkl}^0 , shown in Equation 1.

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^0}{d_{hkl}^0} \quad \text{EQUATION 1}$$

Residual stress was then determined using Hooke's law, Equation 2.

$$\sigma_a = \frac{E}{(1 + \nu)(1 - 2\nu)} [\varepsilon_a(1 - \nu) + \nu(\varepsilon_b + \varepsilon_c)] \quad \text{EQUATION 2}$$

This calculation is conducted for the three assumed principal directions, leading to determinations of σ_{xx} , σ_{yy} and σ_{zz} .

RESULTS

Profilometer Measurements

All three samples bowed after removal, as predicted through the use of the arch geometry, and the Solaris LaserScan measurements revealed the highest distortion in the chess sample (shown in Fig. 5). Although the distorted shape exaggerates the raised edges, these are an artifact of the SLM process and not distortion after removal – they can be seen in the pre-removal data as well. Thus a fairly symmetric bowing is observed along the x-dimension of the sample, and a centerline profile can be used to characterize the shape.

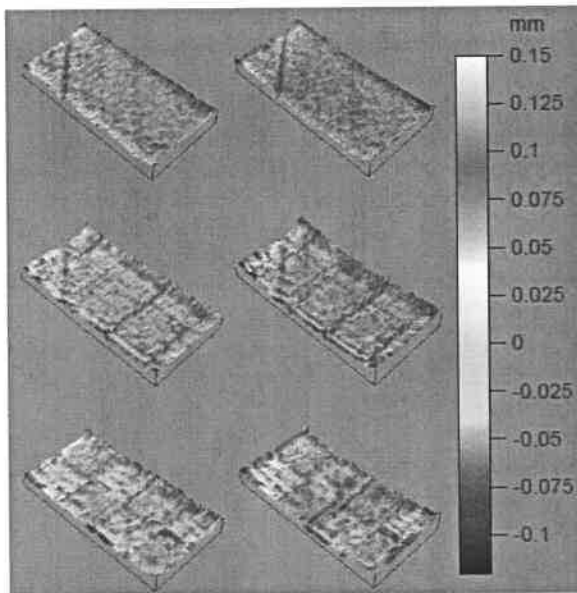


FIGURE 5. Surface Profilometry Results

Fig. 6 shows an example of the distortion seen in a centerline profile before and after removal (sample B3). Form calculation using a polynomial order 2 can characterize the shape of the bowing and gives an indication of the extent of distortion. The precision of the form calculation can be evaluated through comparison of the “before” profile and the “after” profile with the form removed – as shown in Fig. 7, this results in virtually identical profiles. The form profiles of 6 samples before- and- after being cut from the baseplate are shown in Fig. 8. The greatest distortion was observed in the

chess samples, followed by island and continuous. This is contrary to the hypothesis of chess generating lower distortions, as well as the measurements made by Kruth [3].

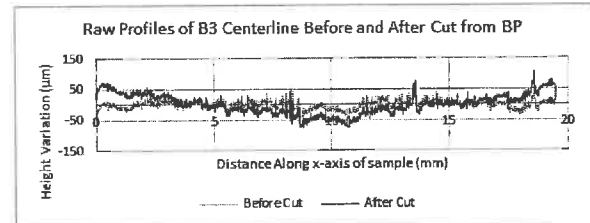


FIGURE 6. Sample B3 Centerline Profiles Before and After Sample was Cut from Baseplate

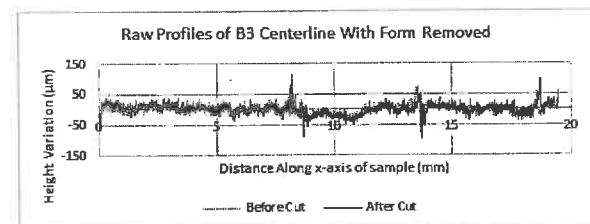


FIGURE 7. Sample B3 Centerline Profiles Before and After Sample was Cut from Baseplate – Form Removed from “After” profile

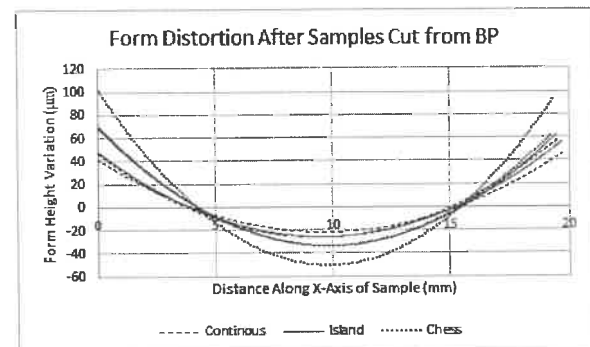


FIGURE 8. All Samples Cut from Baseplate - Form Distortion

To compare these distortions to Kruth's [3], tangent lines were used to find the angle of distortion. Results are shown in Table 2. The profilometer data taken in this research clearly shows a different trend than that taken in Dr. Kruth's, and the previous hypothesis that island and chess strategy consistently reduce distortion is shown to be incorrect.

TABLE 2. Measured Angles of Distortion

Sample	Measured Angle
Kruth 5mm Island (Ti64)	2.65°
Kruth Continuous (Ti64)	2.8°
A1: Continuous	1.54°
A2: Continuous	1.82°
B1: Island	1.82°
B2: Island	2.34°
C2: Chess	3.52°
C3: Chess	2.42°

Volumetric Residual Stress Measurements

The volumetric residual stress measurements showed the highest tensile stresses in the continuous sample, followed by island, and lowest in chess – see Figs. 9-11.

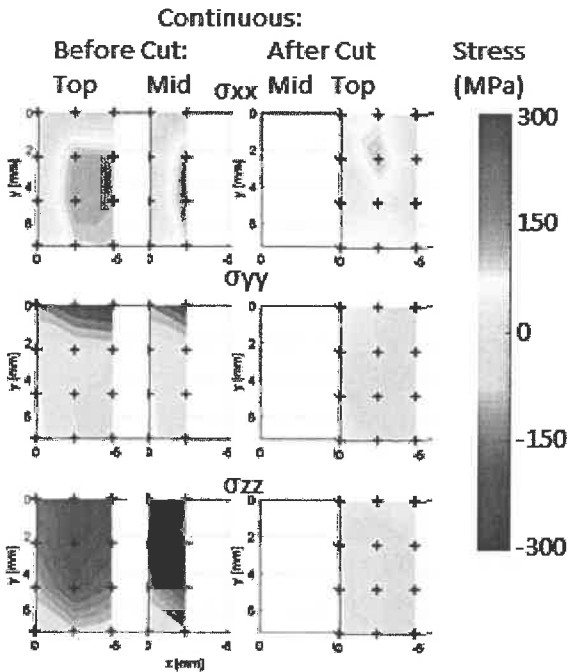


FIGURE 9. Continuous Sample (a) Before Removal and (b) After Removal

The anticipated x-direction tensile stresses are present when the samples are attached to the baseplate, and these stresses relieve significantly when the sample is removed and allowed to distort, to the point where they are very near zero for the chess sample.

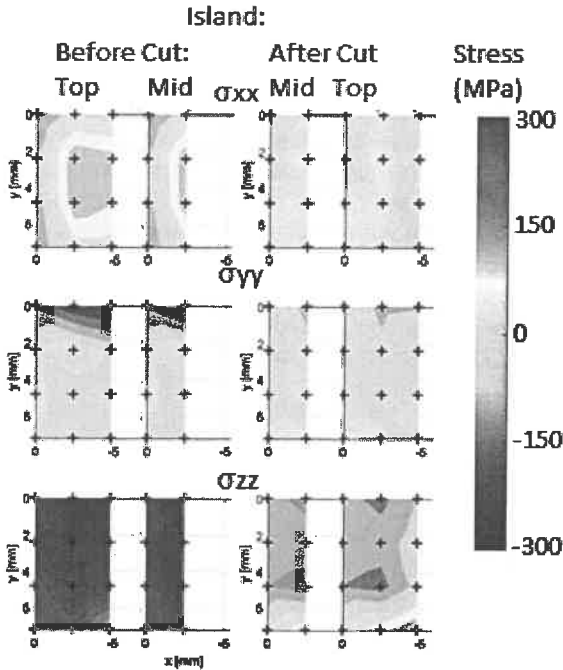


FIGURE 10. Island Sample (a) Before Removal and (b) After Removal

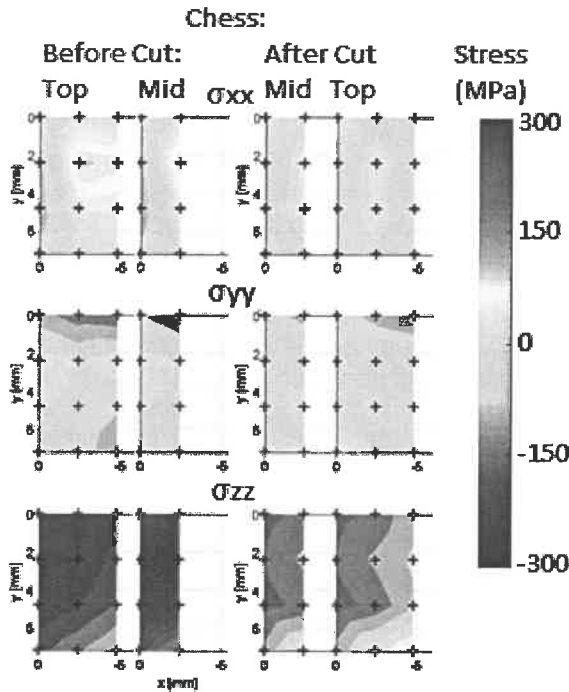


FIGURE 11. Chess Sample (a) Before Removal and (b) After Removal

High compressive stresses are seen in the z-direction, which is contrary to what was found in the initial study where z-direction stresses were tensile or close to zero. Once the sample is removed, these stresses are also relieved, but in this case the continuous sample nears zero stress while the chess and island samples retain some compressive stresses (with chess being highest in magnitude). This could be due to the stresses generated from the interlocking of the segments, which would not be relieved through sample removal and would be most severe in the chess sample.

CONCLUSION

Measurements clearly show the highest distortion (due to removal from the build plate and relieving residual stresses) in the chess sample, through evaluating both surface profilometry and a line scan down the center of the sample. This was not expected and inconsistent with previous work [3], and should be investigated further.

The tensile residual stresses in the x-direction were highest in the continuous sample, followed by island and chess, but the compressive residual stresses in the z-direction were highest in the chess sample, followed by island then continuous. This may be due to the binding nature of the segments.

FUTURE WORK

Although the shape of the arch lent itself to generation of higher residual stresses, the small size of the samples made volumetric measurement using neutron diffraction challenging. The smallest gage volume that could be reasonably utilized was 2 mm³, in order to have enough grains in the gage volume, and so the top of the arch could not be evaluated while ensuring gage volume burial. A similar shape but larger sample would be desirable to evaluate.

It is additionally recommended to conduct a follow-on study regarding build interruptions and their effect on residual stresses - the abnormal results from the initial study are likely due to the build interruption, since results from this study align closer with other residual stress research.

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ANISOTROPIC TENSILE TESTING OF ADDITIVELY MANUFACTURED PARTS WITH VARYING INTERIOR RASTER GEOMETRIES BY LOW-COST FUSED FILAMENT FIBRICATION MACHINES

Brennan E. Yamamoto¹, and A Zachary Trimble¹
¹RIP Laboratory, Department of Mechanical Engineering
University of Hawai'i at Mānoa
Honolulu, HI, USA

ABSTRACT

Fused Filament Fabrication, FFF (also known by its tradename, Fused Deposition Modeling), is an additive manufacturing (AM) process commonly used for geometric modeling and rapid prototyping of parts. Recent consumer interest in FFF has motivated research into improving the strength of manufactured parts to for use-cases outside of rapid prototyping. In this work, ASTM D638-compliant tensile tests are performed to characterize the relationship between the interior raster geometry, and the anisotropic tensile strength of FFF parts using polylactic acid (PLA) thermoplastic. These experiments show that the more complex hexagonal interior raster geometry increased yield stress by up to 5 MPa at low infill densities, indicating that geometric design complexity available in AM can be used to improve part performance. In this testing we also show that the anisotropic tensile strength performance from low-cost FFF machines (75-80% difference between tensor components) is substantially inferior to industry-level FFF solutions (10% difference between tensor components). This paper discusses possible solutions to this issue, and proposes future work based on these results.

INTRODUCTION

With the recent onset of low-cost (<\$2000) FFF machines, the interest in the scope of FFF has expanded to include final end-use parts in addition to rapid prototyping. This has motivated research into the strength characteristics of AM parts by FFF. Existing literature has found that FFF is generally inferior to injection molded and traditionally (subtractive) manufactured parts, and is subject to highly anisotropic behavior [1]–[12]. Despite this, FFF enables complex part geometries that, for a well-designed part, lead to increased part functionality and performance that outweigh the strength trade-offs [13].

A common FFF technique that takes advantage of geometric complexity, is varying the density of the interior raster (infill) of the printed part to reduce material consumption; this is very simple for FFF parts but is nearly impossible using traditional manufacturing techniques. In past work by [1], a design-of-experiments analysis showed that the two most sensitive process parameters to tensile strength are the air gap (density), and orientation of the interior raster toolpaths. The primary objective of this study is to investigate how varying the geometry and density of the interior raster toolpath influences the anisotropic tensile strength of polylactic acid (PLA) thermoplastic material.

In part one of this work, a low cost (<\$2000) Artifex 2 FFF 3D printer was used to print ASTM D638-compliant, PLA test samples; a Stratasys Uprint FDM machine was also used for benchmarking samples. The rectilinear and hexagonal (“honeycomb”) infill densities were tested at densities ranging from 20% to 100% using the ASTM D638 tensile test standard. These parts were printed in both the ‘facedown’ (parallel to the build plane) and ‘upright’ (orthogonal to the build plane) orientation. The tests show that the more complex hexagonal facedown samples demonstrated samples demonstrated up to 5 MPa greater yield stress than the rectilinear facedown samples at low interior raster densities; which converged as the density approached 100%. Conversely, the upright samples did not demonstrate a significant difference between the hexagonal and rectilinear interior raster geometries.

In part two of this work, the anisotropic tensile strength characterization was evaluated by comparing the *fracture stresses* of the facedown samples against the upright samples. On average, the Artifex 2 upright tensile samples demonstrated 21-36% the fracture stress of the facedown samples, whereas the Uprint produced upright samples with 89% the fracture stress of the facedown samples. A discussion

hypothesizing an explanation for this difference is made in the conclusion.

THEORY

In FFF, a three dimensional model is created by extruding a continuous bead of molten material through a CNC-hotend to form layers of deposited material. A schematic of a typical extrusion assembly is shown in FIGURE 1.

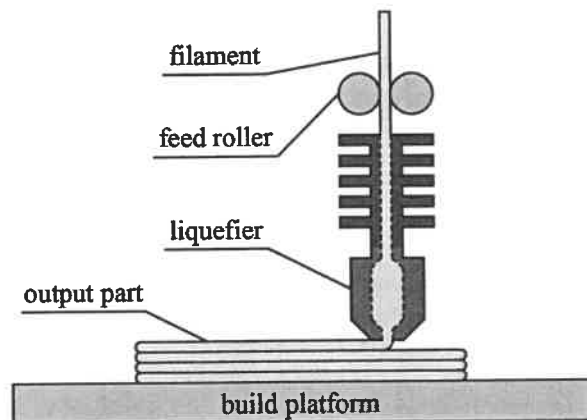


FIGURE 1: Fused Filament Fabrication extrusion process.

Material

FFF operates by melting a solid material into liquid form, which allows the machine to deposit the material in space while still malleable. Thusly, FFF lends itself particularly to materials that are capable of repeated melt and harden cycles, particularly thermoplastics. Among these, the most common materials are acrylonitrile butadiene styrene (ABS), and more recently, polylactic acid (PLA). Compared to ABS, PLA has a lower melt temperature, lower thermal expansion, higher tensile strength and is biodegradable [14]. For these reasons PLA has gained much popularity as a material choice in the low-cost, consumer FFF market. Because of the abundance of existing FFF research using ABS, PLA was chosen as the thermoplastic for this study.

Toolpath and Process Parameters

The extruder toolpaths and process parameters are determined beforehand in a software process called "slicing". This process takes a 3D model, usually a stereolithography (.stl) format file, and converts it into machine language based on a comprehensive set of user-configurable process parameters, e.g. layer thickness, extrusion width, infill and support structure pattern and density, speed, temperature flowrate, etc. In past work by [1], a design-of-

experiments analysis of FFF/FDM showed that the two most sensitive process parameters to tensile strength are related to the interior raster of the part; particularly, the air gap (density), and orientation of the interior raster toolpaths. Thusly, toward the design goal of maximizing tensile strength, this work will primarily focus on process parameters related to toolpath optimizations.

In any given layer, the extrusion toolpath falls into one of four regimes: (1) support material (2) wall material, (3) floor and ceiling material, and (4) interior raster (infill) material. Firstly, support material is sacrificial material used to support external overhanging features on the part that would otherwise sag due to gravity as the material solidifies. Because support material is removed from the part in post-processing, it has no effect on the tensile strength of the final part. Secondly, wall material is continuous path of material parallel with the outer edge of the model at each layer, and may repeat any number of times (specified by the user) concentrically inward. Thirdly, floor and ceiling material fully fills the area inside the concentric wall material on the top and bottom surfaces of a part. Finally, the interior raster material fills any interior regions of the part not consumed by floor, ceiling or wall material; the user has the option of choosing the infill pattern, pattern angle (orientation), and infill density. These toolpath regimes are shown in FIGURE 2.

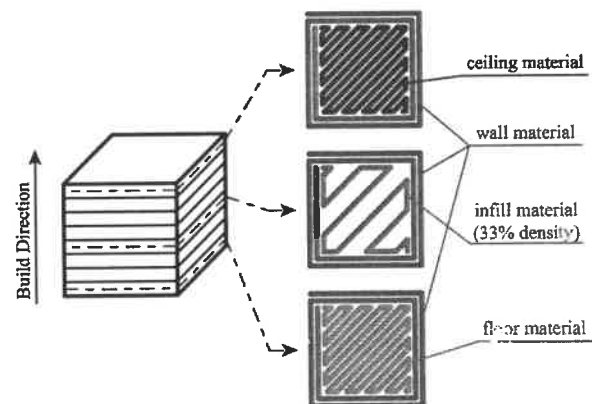


FIGURE 2: Toolpath regimes for an example part.

Interior Raster Geometry and Density

As previously discussed, a common technique in FFF is to reduce the density of the interior raster to reduce material consumption and weight of the final part. Most often, this is done with the rectilinear infill pattern shown in FIGURE 3.

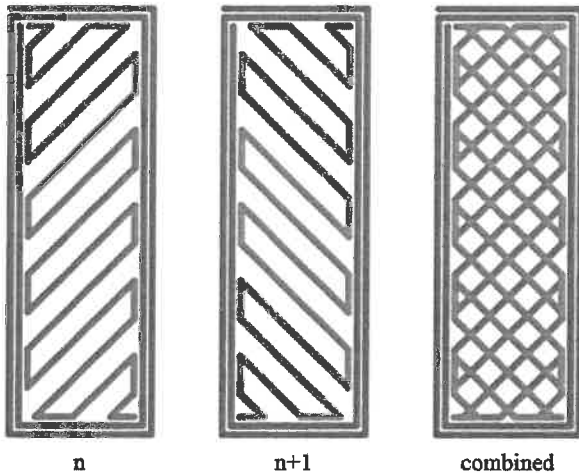


FIGURE 3: Rectilinear interior raster toolpath example. The infill pattern is repeated every two layers.

Another common, but more complex interior raster geometry is the hexagonal (honeycomb) toolpath. Although the hexagonal geometry adds more manufacturing complexity, the Honeycomb Conjecture [15] proposes that a hexagonal raster structure provides superior perimeter to empty area ratio. An illustration of the hexagonal toolpath is shown in toolpath shown in FIGURE 4.

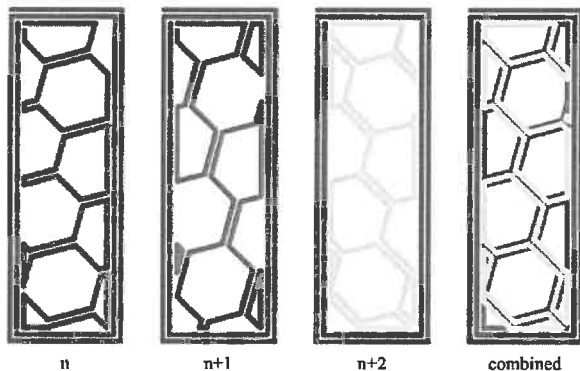


FIGURE 4: Hexagonal (honeycomb) interior raster toolpath example. The infill pattern is repeated every three layers.

The first experiment in this study is to investigate whether increasing the complexity of a FFF part by changing from a rectilinear to hexagonal interior raster will have a meaningful effect on the strength of the final part.

Anisotropic Tensile Strength

In past work, it has been shown that the layered nature of the FFF process results in anisotropic tensile strength of finished parts [1]–

[3], [5], [6], [8], [9], [12]. When the direction of the tensile load is applied parallel with the layer plane (facedown), FFF parts behave as a ductile material with a well-defined elastic and plastic stress regimes; conversely, when the direction of the load is applied orthogonal to the layer plane (upright), the parts demonstrate brittle failure with no defined yield and ultimate tensile stress (strain <1%) [1], [12]. Despite the general agreement that FFF parts demonstrate anisotropic tensile behavior, the stress tensor components reported in existing literature vary significantly, i.e. 50-60% [12], 65% [2], 58% [9], and 99% [8], and have only been comprehensively tested with ABS and polycarbonate working materials. Thusly the second experiment in this study was to compare the tensile strength of facedown and upright samples from the Artifex 2 in both PLA and ABS, and an industry-level Stratasys Uprint FDM machine.

EXPERIMENTAL SETUP

Part 1: Infill Density vs. Tensile Strength

The tensile tests in this experiment are compliant to the ASTM D638-14 standard test method for tensile properties of plastics. To best capture the effect of the interior raster, Type III dogbone samples were chosen for their large gauge cross section. The machine used was a 3DMakerWorld Artifex 2 printer. The open-source slicing software, Slic3r was used with the following process parameters:

- layer height: 0.2 mm
- extrusion width: 0.5 mm
- wall layers: 1
- horizontal (ceiling and floor) layers: 3/3
- speed: 60mm/s
- interior raster: rectilinear and honeycomb
- interior raster density: 20-100%
- interior raster fill angle: 45°/45°
- material: Hatchbox PLA, white, 1.75mm diameter

At least three samples were taken at each tested infill density. Particularly variable tests were run multiple times.

Part 2: Anisotropic Tensile Strength Testing

The tensile tests in this experiment are compliant to the ASTM D638-14 standard, this time using the smaller Type I dogbone samples to satisfy the build volume constraints in the Uprint. This experiment looks at six different machine-material-orientation combinations: The Artifex 2 in Hatchbox PLA and 3DMakerWorld

ABS with facedown and upright orientations, *and* as the Uprint in ABS P430 in facedown and upright orientations. The Artifex 2 utilized the same process parameters and slicing software as in Part 1; the Uprint used its proprietary software and default process parameters. All samples were printed at 100% interior raster density.

RESULTS

Part 1: Infill Density vs. Tensile Strength

FIGURE 5 through FIGURE 8 plot the various tensile stress parameters for each sample type as a function of filament length. Note that filament length is linearly proportional to interior raster density. Filament length was chosen over interior raster density because the Slic3r software systematically added more material to the hexagonal samples, despite slicing at the same interior raster density as the rectilinear samples; plotting against filament length normalizes out this systematic variable. Note that yield and ultimate tensile stresses do not exist for the upright samples due to their brittle failure mode. FIGURE 9 through FIGURE 12 then plots the same tensile stress parameters against total print time.

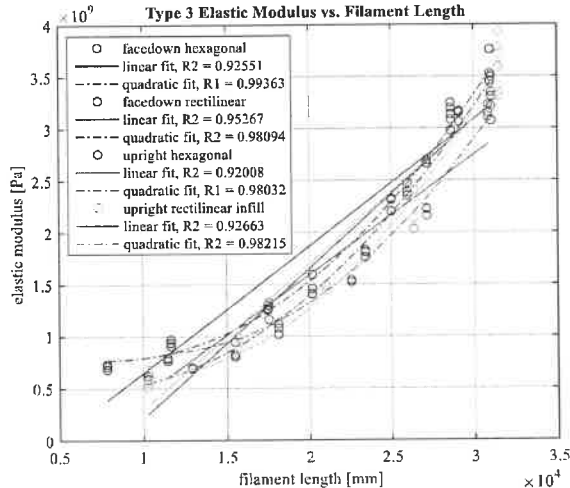


FIGURE 5: Elastic modulus vs filament length.

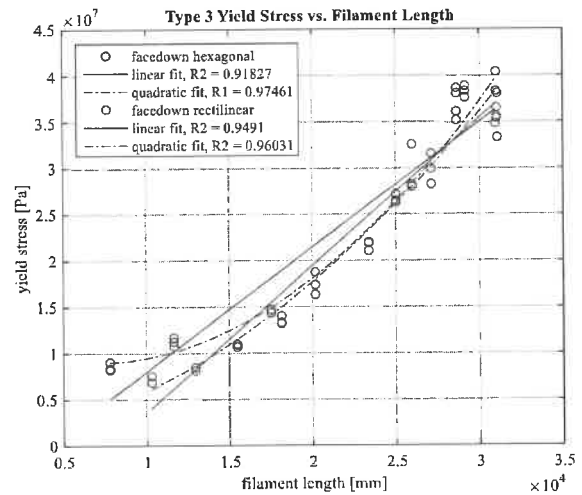


FIGURE 6: Yield stress vs filament length.

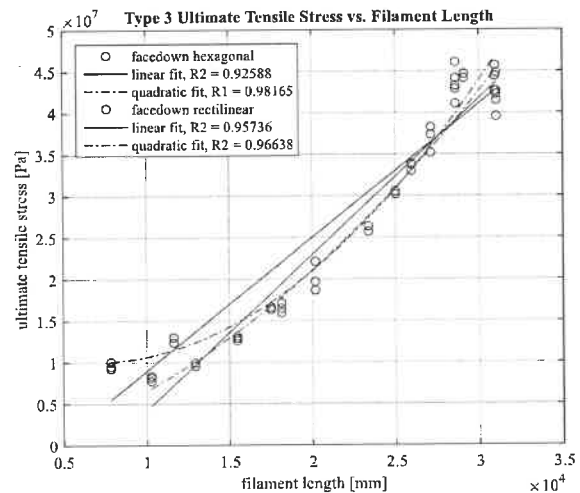


FIGURE 7: Ultimate tensile strength vs filament length.

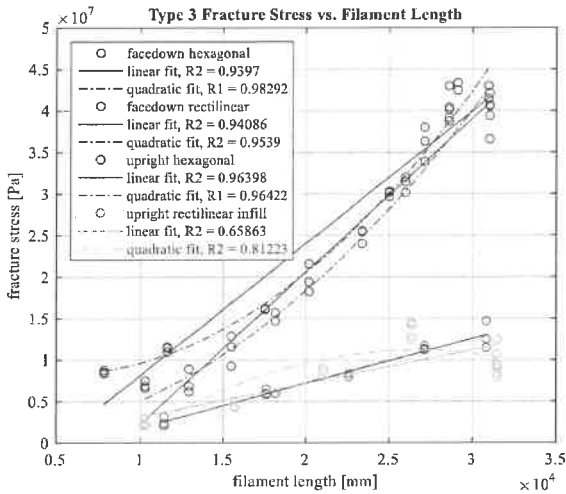


FIGURE 8: Fracture stress vs filament length.

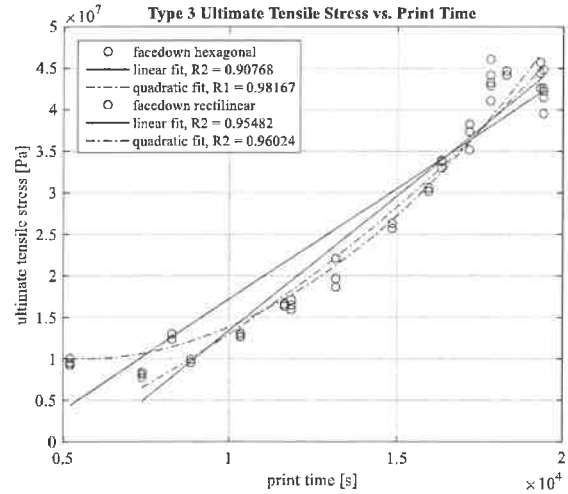


FIGURE 11: Ultimate tensile stress vs print time.

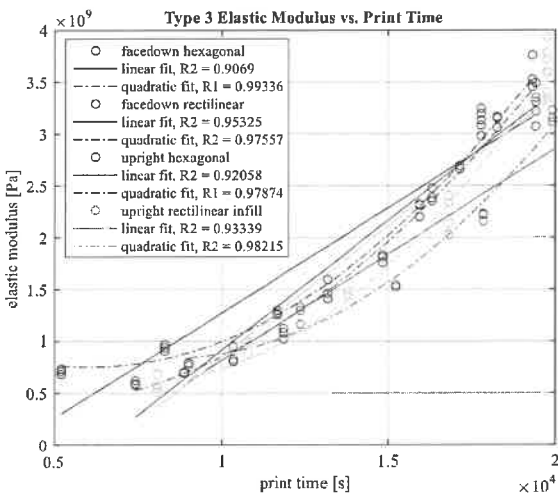


FIGURE 9: Elastic modulus vs print time.

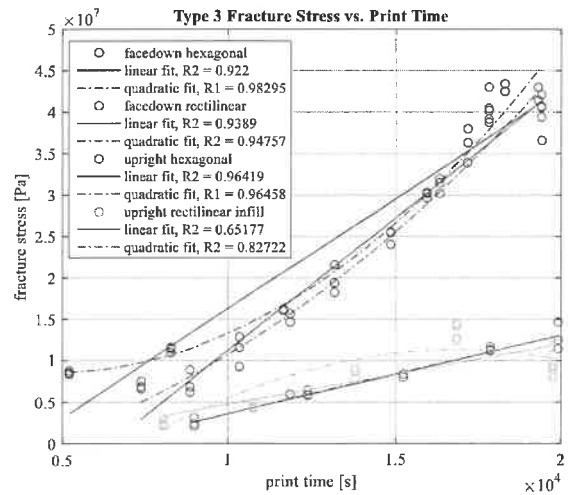


FIGURE 12: Fracture stress vs print time.

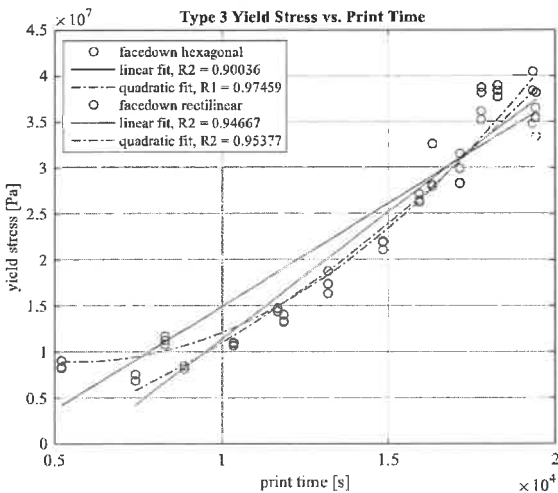


FIGURE 10: Yield stress vs print time.

Part 2: Anisotropic Tensile Strength Testing

FIGURE 13 plots the average elastic moduli for all six machine-material-orientation combinations. FIGURE 14 plots the average tensile strengths for all six machine-material-orientation combinations. Note that the upright samples demonstrated brittle fracture, and thus, do not have a defined yield and ultimate tensile stress.

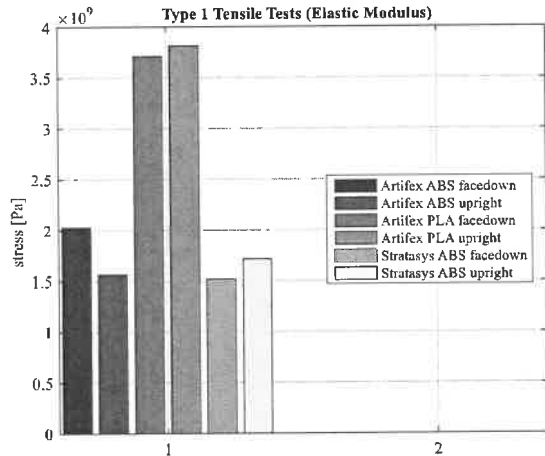


FIGURE 13: Elastic moduli of Type 1 tensile samples.

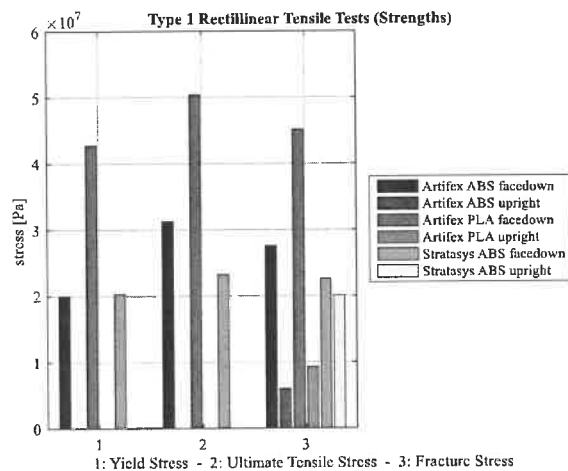


FIGURE 14: Elastic moduli of Type 1 tensile samples.

CONCLUSIONS

The results from Part 1 reveal multiple interesting results. First, the elastic modulus (stiffness) remains relatively constant regardless of the print orientation, despite the fact that the strength parameters dramatically decrease in the upright orientation. Second, we can clearly see that the facedown hexagonal infill parts have a noticeable (≈ 5 MPa) strength advantage over the facedown rectilinear parts at low infill densities; however, as the infill density approaches 100%, the tensile strengths converge, which seems to indicate that the increased perimeter-to-area optimality provided by the hexagonal raster does result in increased part strength. Third, the upright samples do not appear to favor either of the infill patterns. Fourth, in three out of the four

orientation-infill combinations, raster densities in the range of 80-90% appear to provide tensile strengths equal to or greater than at 100%. This may be attributable to increased internal stresses present in 100% density parts; however, at the time of writing, the author does not have a clear explanation for this phenomenon. Fifth, barring the phenomenon just discussed, the relationship between all of the y-axis parameters and infill density/filament length is relatively linear. In most cases, the positive quadratic fit does produce a better $\overline{R^2}$ value, but this mild nonlinearity is not particularly meaningful. Fifth, print time does not meaningfully affect any of the above conclusions, taking into account print time mildly 'improves' the simpler toolpath geometry of the rectilinear samples, but does not do so in a way that would necessitate significant design tradeoffs.

The results from Part 2 also reveal a particularly interesting result. First, the Artifex 2 produces upright fracture stresses that are 21% (PLA) and 22% (ABS) of their respective facedown fracture stresses, whereas the Uprint produces an upright fracture stress that is 89% of its facedown fracture stress. Given that the Artifex 2 produces similar results for both ABS and PLA, it is more likely the case that the Uprint is taking advantage of a process parameter/feature not available on the Artifex 2.

Based on the results from this study, there are multiple avenues of future research. The primary deliverable of this study was to substantiate the idea that part complexity available in AM can be used to increase the performance of the final part. Given that we have shown that part performance can be increased by a trivially simple change in your process parameters, this has clearly been shown to be the case. Secondly, there is clearly improvement to be made the anisotropic strength of parts from low-cost FFF machines. Research in improving delamination strength, e.g. [16], may enable the next big improvement in low-cost FFF manufacturing.

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X-RAY COMPUTED TOMOGRAPHY FOR ADDITIVE MANUFACTURING: ACCURACY OF POROSITY MEASUREMENTS

Petr Hermanek¹, Filippo Zanini¹, Simone Carmignato¹ and Enrico Savio²

¹Department of Management and Engineering

University of Padova

Vicenza, Italy

²Department of Industrial Engineering

University of Padova

Padova, Italy

INTRODUCTION

The great potential of Additive Manufacturing (AM) techniques in production of complex structures (both internal and external) with almost unlimited design freedom [1] is affected by inherent imperfections, such as internal porosity, due to the AM process itself [2-3]. These internal defects are, apart from some special applications (e.g. biomedical applications), unwanted since they directly influence mechanical properties of a final product [4]. As they cannot be completely removed, knowing the information about the defects shape, size and distribution becomes crucial.

Recently, X-ray Computed Tomography (CT) has emerged as an advanced tool for dimensional measurements of both internal and external features as well as for porosity evaluation [5-6]. Thanks to its capability of investigating and measuring internal defects in a non-destructive way, CT can overcome some important limitations of other well-established methods, such as Archimedes method and microscopic analysis of cross-sections [7-8]. The first provides only information about the total porosity content and the latter is limited to a certain number of cross-sections, which can distort the overall result. Although CT has already been established in industry as an alternative method for internal defects analysis, assessing the accuracy of CT porosity evaluation is still a challenging task [9].

In this work, as the first step, CT porosity analysis is compared to volume-based Archimedes method and area-based microscopic analysis of cross-sections, by experiments performed on Ti6Al4V tensile specimens produced by Selective Laser Melting (SLM). Specific cross-sections are further

analyzed by means of a high accuracy multisensor CMM using an image processing sensor to get reliable reference values for pores area. In the second step, the performance of computed tomography in porosity measurements is assessed by evaluation of measurement errors using a newly developed reference object with artificial defects.

EVALUATION TECHNIQUES AND INSTRUMENTS

CT data throughout this publication were obtained by a metrological CT system with maximal acceleration voltage of 225 kV, temperature controlled cabinet and 16 bit flat panel detector (2000×2000 pixels). The maximum permissible error (MPE) for length measurements of the CT system is $MPE = 9 + L/50 \mu m$ (L is the length in mm). The acquired CT data was elaborated in software VGStudio MAX 2.2.6.

Comparison of CT porosity analysis to volume- and area-based methods

The comparison of methods was investigated through analyses performed on Ti6Al4V tensile specimens (each with maximum diameter equal to 10 mm) manufactured by SLM. Different percentages of internal porosity were achieved by variations of process parameters.

Relative densities were determined both by CT and by Archimedes volume-based method and then compared.

Furthermore, porosity calculated by microscopic area-based analysis of cross-sections was compared with CT porosity, following a new designed procedure: specimens were CT scanned before and after cutting/polishing operations, in order to (i) analyze in the CT volume exactly the same cross-section analyzed

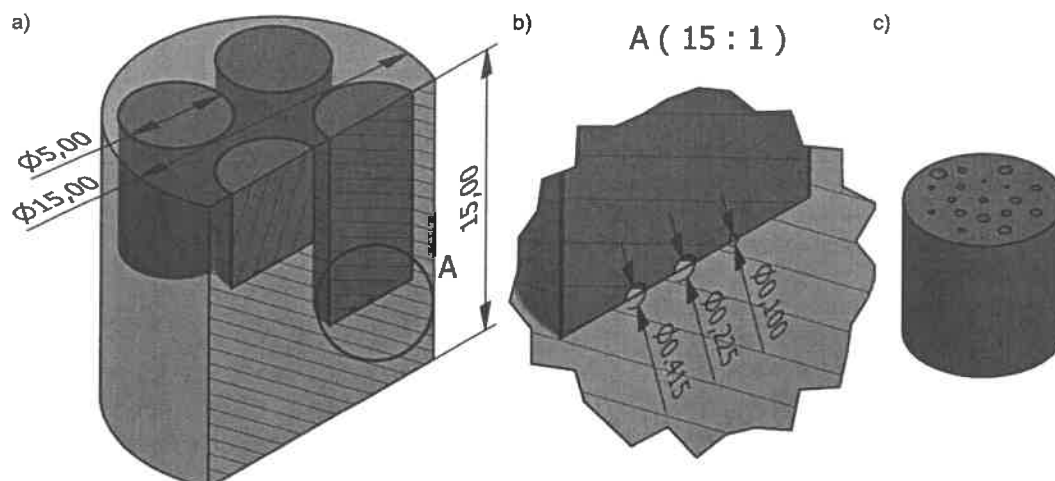


FIGURE 1. Schematic representation of the newly designed reference object (dimensions in mm). (a) Complete assembly with general dimensions, (b) detail of the artificial defects, (c) dismountable pin including 18 hemispherical calottes with diameter ranging from 100 to 500 μm .

by microscopic analysis and (ii) to compare CT results obtained before and after cutting the samples. To complete the comparison, reliable reference values for the areas of specific pores lying on the cut-sections of interest were obtained by a multisensory CMM equipped with image processing sensor (Werth Video-Check-IP 400; $\text{MPE} = 1.8 + L/250 \mu\text{m}$, with L in mm).

Evaluation of CT performance in porosity measurements

The approach to evaluate the CT porosity measurement errors through a reference object with artificial defects was used in this publication. The composition of the reference object was designed considering three main requirements: (i) the material of the object should be suitable for CT scanning (i.e. should have rather low attenuation coefficient), should provide sufficient metrological stability and at the same time should be widely applied in industry; (ii) the internal defects in the mounted state should be completely internal and (iii) the internal defects must allow calibration by external (conventional) measurement instruments. Based on the requirements, the reference object was defined as schematically depicted in Figure 1 [10]. All components of the object are made of aluminum and the object comprises hemispherical features resembling the artificial internal defects. These calottes are milled onto faces of dismountable cylindrical inserts enabling the calibration by conventional instruments. The cylindrical body, in which the cylindrical inserts (5 mm in diameter) are mounted, has 15 mm in diameter and is 15 mm

high. The size range of the milled calottes is 100 – 500 μm and each insert contains 18 of them resulting in 72 defects in total. Furthermore, in order to ensure more random distribution of the defects, the height varies among the pins as can be seen in Figure 1.

The reference values of diameter, depth and volume of each calotte were acquired by three different measuring systems: (i) the multisensory CMM equipped with image processing sensor presented in the previous section, (ii) profiler using confocal microscopy in 20 $\times$ magnification and (iii) the CT system for scanning single pins in 60 $\times$ magnification. The reference object was scanned 12 times under the same conditions in order to assess, in addition to measurement errors, also repeatability of measurements.

RESULTS

Relative densities determined by the Archimedes method were found to be systematically lower than the CT-measured densities, but with a similar trend, as can be observed in Figure 2.

These systematic deviations can be attributed to the intrinsic limits of both methods. On one side, the nominal material density, used as reference for Archimedes' relative density evaluation, cannot be considered reliable, especially for non-homogeneous parts. On the other side, CT measurements can be influenced by image artefacts due to the interaction between X-rays and material, by the resolution (e.g. pores with size lower than the spatial resolution cannot be detected) and by the thresholding procedure.

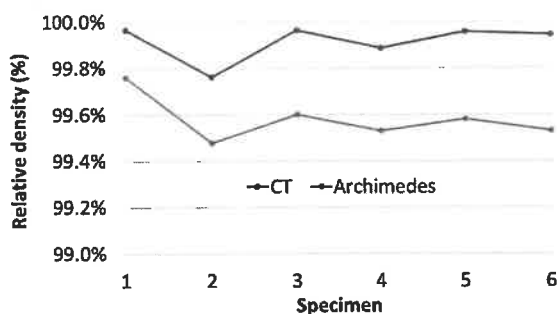


FIGURE 2. Comparison of relative densities measured through CT and Archimedes method.

The comparison between CT and microscopic analysis of cross-sections resulted in a systematic difference as well. In particular, results by microscopic analysis are very close to the CMM results, while CT always measured smaller areas (Figure 3a). If CT is influenced by the above-cited factors, micrographs can be affected by light and focus settings, stitching operations, thresholding and binarization.

A systematically lower area measured by CT post-cut with respect to CT pre-cut can be observed with regard to the cut-section. Possible causes were identified in (i) deformations due to cutting/polishing operations and (ii) presence of entrapped unmolten powder residue that may fall out during the cutting (Figure 3b). A number of internal cross-sections (not affected by the cut) were also considered and no difference was found.

The results of experiments performed on the reference object are shown in Figure 4, where errors of diameter and depth measurements are plotted and in Figure 5, where relative errors of volume measurements are depicted. The investigation showed that in case of diameter and depth, errors below $5\text{ }\mu\text{m}$ and below $3\text{ }\mu\text{m}$

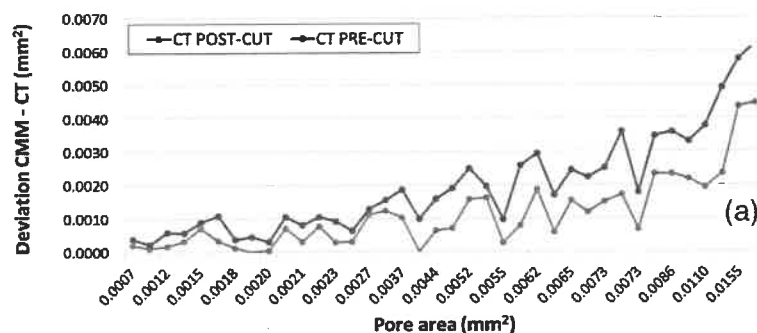


FIGURE 3. Example of deviations between pore areas measured by multisensor CMM and CT (pre and post cut) on Ti6Al4V specimens (a). SEM image of a pore with unmolten powder residue inside (b).

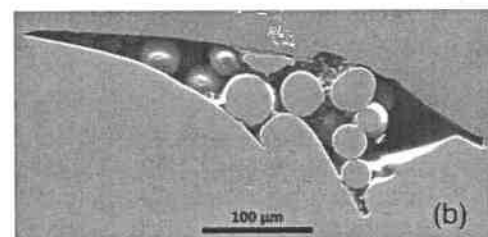
respectively are achievable. In case of volume measurements, the relative error was below 5 % for major part of the defects. However, the errors in case of defects smaller than $200\text{ }\mu\text{m}$, especially in diameter measurements, are significantly higher (see Figure 4). Considering, that the increase in diameter measurement error towards smaller defects is compared to other measurands abruptly higher, the reason can reside in insufficient number of acquired points during calibration by optical instruments.

Figures 4 and 5 show also error bars which represent ± 1 standard deviation of 12 repeated measurements. The results show that, apart from the smallest defects, the standard deviation can be below $2.5\text{ }\mu\text{m}$ in case of diameter, below $2\text{ }\mu\text{m}$ for depth and below 2 % for volume measurements.

CONCLUSIONS

From the experimental investigations resulted that systematic errors exist between the different applied methods for porosity evaluation. In particular, CT leads to densities which are higher by 0.2 – 0.4 % than Archimedes results. As far as the area-based porosity analysis concerns, CT measured pore areas were found to be always smaller than optical measurements. Several causes were discussed in the previous section. Notably, the presence of unmolten powder residues and deformations due to the cutting/polishing operations were identified as the reason of deviations between CT results before and after cutting the specimens.

The results obtained by scanning the newly developed reference object showed that for larger defects errors below $5\text{ }\mu\text{m}$ and below $3\text{ }\mu\text{m}$ can be achieved for diameter and depth measurements respectively.



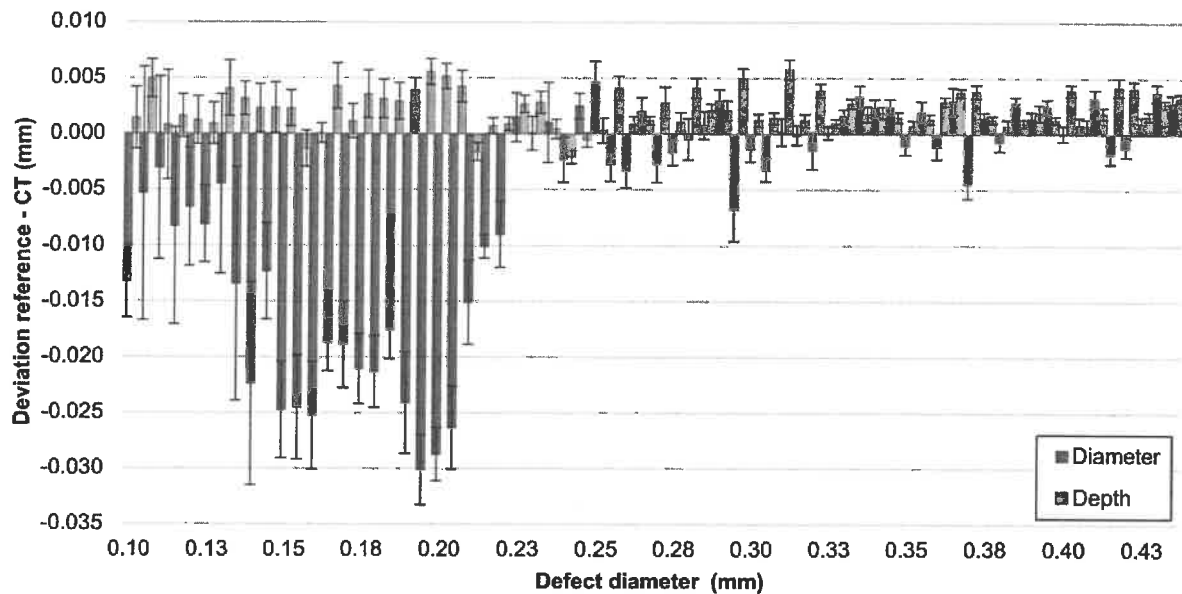


FIGURE 4. Evaluation of diameter and depth measurement errors using the newly designed reference object. The analysis was performed on all 72 defects. Error bars represent ± 1 standard deviation of 12 repeated measurements.

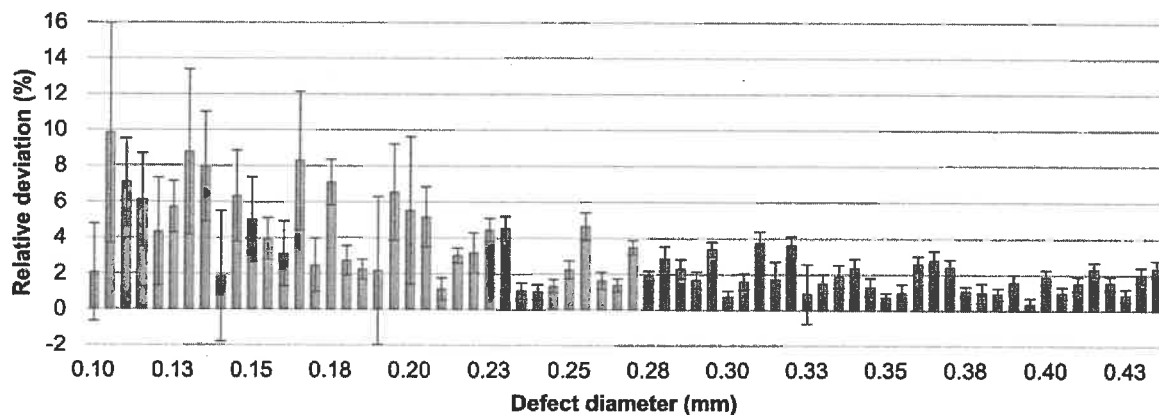


FIGURE 5. Evaluation of volume measurement errors using the newly designed reference object. The analysis was performed on all 72 defects. Error bars represent ± 1 standard deviation of 12 repeated measurements.

Errors in case of volume measurements were below 5 % except for the smallest defects. Standard deviations extracted from the study on repeatability of measurements were below $2.5 \mu\text{m}$ for diameter, below $2 \mu\text{m}$ for depth and below 2 % in case of volume measurements. The rapid increase of measurement error for small defects, especially in case of diameter measurements, can be caused by insufficient number of collected points during the calibration. Improvement of calibration methods is subject of ongoing research.

ACKNOWLEDGEMENTS

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ASSESSING THE STRUCTURAL INTEGRITY OF ADDITIVE MANUFACTURED METAL PARTS WITH X-RAY CT

Herminso Villarraga-Gómez¹, Mohsen Seifi², Yusuke Uchiyama³,
Andrew Ramsey⁴ and John J. Lewandowski²

¹Nikon Metrology, Inc., Brighton, MI, USA

²Case Western Reserve University, Cleveland, OH, USA

³Nikon Corporation, Tokyo, Japan

⁴Nikon Metrology, Tring, UK

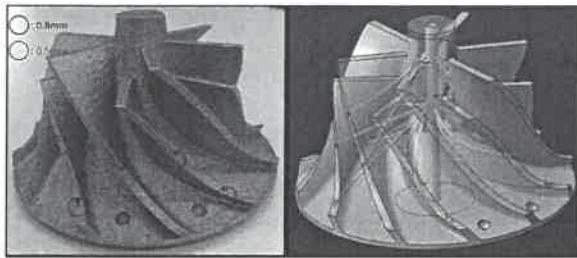


Figure 1. Left: EBM-AM sample of a compressor wheel. Right: 3D CAD volume. It has hollow channels inside with diameters of 0.5 mm and 0.8 mm.

This paper presents a study of structural integrity assessment of the internal features of additive manufactured (AM) metal parts using X-ray computed tomography (CT). Recent work [1]–[3] has shown the significant progression of CT technology as a tool for assessing AM processes since earlier conferences/workshops [4]. While previous work [5] provided some insight for evaluation of dimensional measurements of AM parts made of plastics, this work focuses on both internal structures and metrology of AM metal parts. The prototype parts analyzed in the present work were manufactured by laser-based powder bed fusion (LPBF) as well as electron-beam melting (ERM). Figure 1 shows both optical and 3D CAD volume images of an AM compressor wheel. This part was manufactured using Al-Si-10Mg pre-alloyed powders and the LPBF technique. Specific process parameters include a layer thickness of 30 μm , hatch spacing of about 100–150 μm , average beam velocity of about 2000 mm/s, power of 90–100% of full power (400W) and a preheating temperature of 200°C using typical laser machine processing parameters. The computer-aided design (CAD) model details the internal structures. Although the hollow internal structures shown in Figure 1 are not typically part of conventionally processed

versions of this compressor wheel design, the cavity paths (i.e. with diameters of 0.8 mm and 0.5 mm) were deliberately added in the CAD model in order to demonstrate the integration of AM and CT in the present study. The second part, a cooling water manifold, was made using Ti-6Al-4V pre-alloyed powders and the EBM technique. In particular, process parameters included sequential build layer thickness of 50 μm and a preheat temperature of around 750°C along with typical EBM machine processing parameters. Figure 2 and Figure 3 show optical and CT images of the EBM-AM Ti-6Al-4V cooling water manifold to illustrate both AM and CT capabilities in this complex design. CT scans were acquired by a metrological CT system, the Nikon's MCT 225, which has a maximum permissible error (MPE) equal to $(9+L/50)$ μm (where L is length in mm) [6], in accordance with the VDI/VDE 2630 guidelines [7]. The CT data were processed for part-to-CAD evaluation and void analysis by using VGStudio MAX 2.2, a software from Volume Graphics GmbH [8].

FAILURES OF STRUCTURAL INTEGRITY

The results of CT analyses in Figure 3 reveal powder residues from the AM process located inside internal structures. These types of obstructions are very difficult to assess using typical nondestructive methods and may obstruct the flow of cooling water in the manifold, requiring their removal prior to use. Defects (voids), porosity and cracking, were also detected in the internal structures of the part as shown in Figure 4. These defects, as well as the as-deposited roughness of internal surfaces, may affect the structural and/or functional integrity of the part, as recently reviewed [9]–[13]. Defects can be potent sites for fatigue/fracture initiation depending upon their size, location, and how the part is loaded. In addition, closures at some locations of the internal channels of the AM compressor wheel

were found as shown in Figure 5. Analyses of multiple regions of the AM part showed that such closures only occurred at channel diameters < 500 μm .

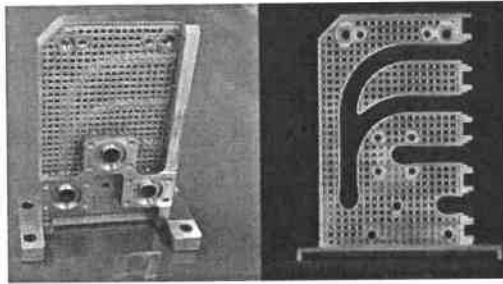


Figure 2. Left: Optical image of LPBF-AM cooling water manifold. Right: CT image.

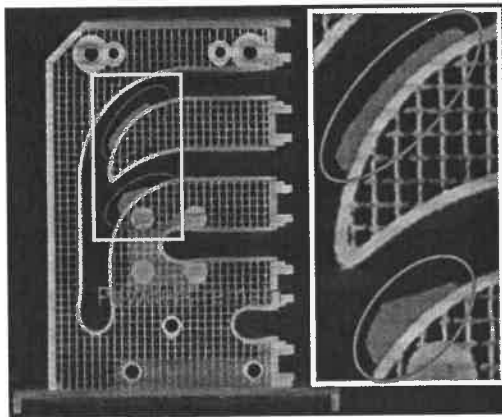


Figure 3. CT image of internal structures showing powder residue that will obstruct path of cooling water.

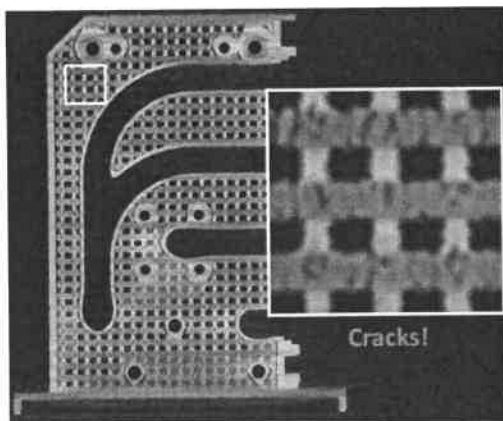


Figure 4. CT image of internal structures of AM cooling water manifold, Figure 2, showing cracks (inset) in as-deposited material.

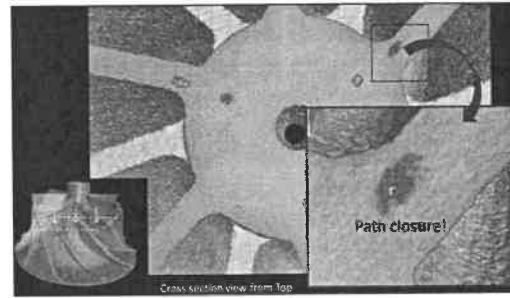


Figure 5. CT image of the internal structures for the AM compressor wheel shown in Figure 1. Inset shows path closures detected via CT.

PART-TO-CAD ANALYSIS

The metrological assessment of the parts was done by part-to-CAD analyses in order to document any departures from the design model of the dimensions of the internal features of the part. The surfaces determined from CT analyses are used as references that are then compared to the original CAD model surfaces. Figure 6 shows deviations of the surface of the cooling water manifold from that of the design in a histogram. The EBM AM part exhibited variations in dimensions, with deviations mostly within ± 0.02 mm of the nominal reference CAD geometry, but larger deviations up to ± 0.1 mm were also detected. Similarly, in Figure 7, the deviations for the AM compressor wheel lie within ± 0.1 mm for most of the surfaces of the part with some sections having deviations up to ± 0.2 mm. These dimensional irregularities are probably caused by phase transformations and residual stresses resulting from the various thermal cycles in the AM process. Further process optimization will be needed to reduce these variations.

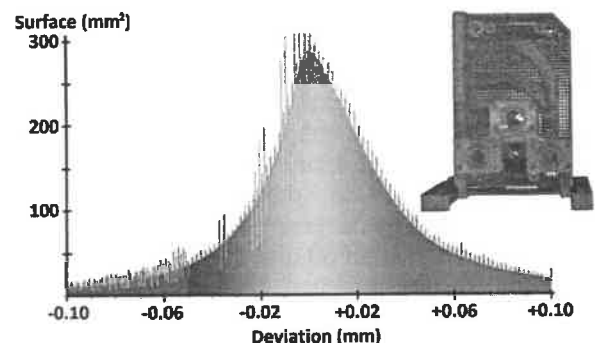


Figure 6. Full variance distribution for deviations of the CAD model in the AM cooling water manifold. Colors on the 3D model correspond to the color-code of the x-axis.

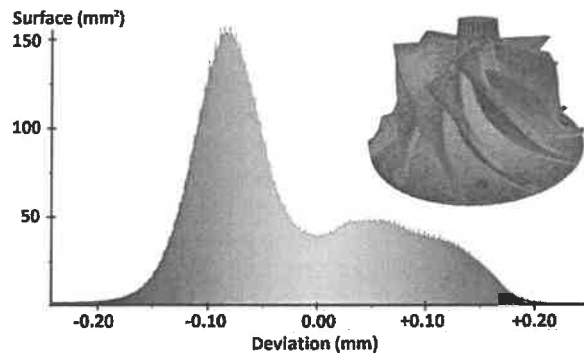


Figure 7. Full variance distribution for deviations of the CAD model in the AM compressor wheel. Colors on the 3D model correspond to the color-code of the x-axis.

VOID ANALYSIS

Currently there is significant interest for testing methods on capabilities/validity of void analysis for metal additive manufacturing [14]–[19]. Although post processing techniques like hot isostatic pressing [12], [20] can be effective in healing/eliminating various types of defects (e.g. porosity, lack of fusion, etc.), in-situ defect detection and mitigation during processing remains a critical task for continuing/future efforts by the AM community. This section aims to assess any porosity or other defects within the AM metal parts. While metrology and dimensional deviation assessments are important as described above, defect(s) analyses are also crucial for fracture-critical components where defect-dominated properties (e.g. fatigue) will be affected. The density distribution of voids in the AM parts was found to be lower for the cooling water manifold than in the compressor wheel, as shown in Figure 8 and Figure 9. Figure 8 shows that the larger pores have a volume of around 0.253 mm^3 , while the maximum void size found was around 1.73 mm . In the case of the AM compressor wheel, although the porosity distribution is larger, the typical size of the voids was found to be smaller, (e.g. 0.001 to 0.022 mm^3), Figure 9. Furthermore, the voids in the compressor wheel were distributed throughout the part with some isolated regions.

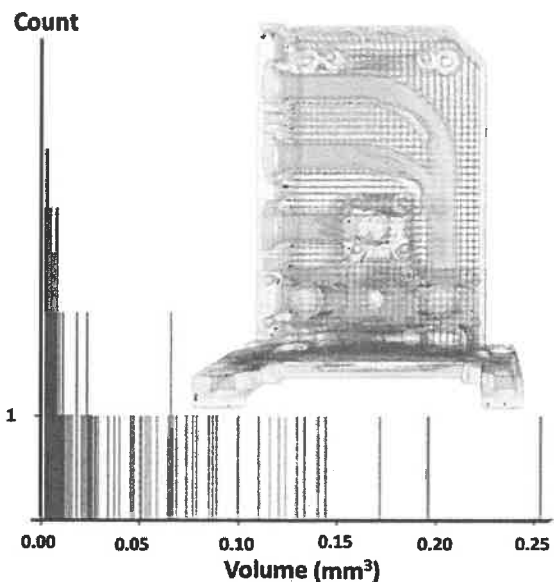


Figure 8. Porosity distribution for the EBM AM cooling water manifold. Colors on the 3D model correspond to the color-code of the x-axis.

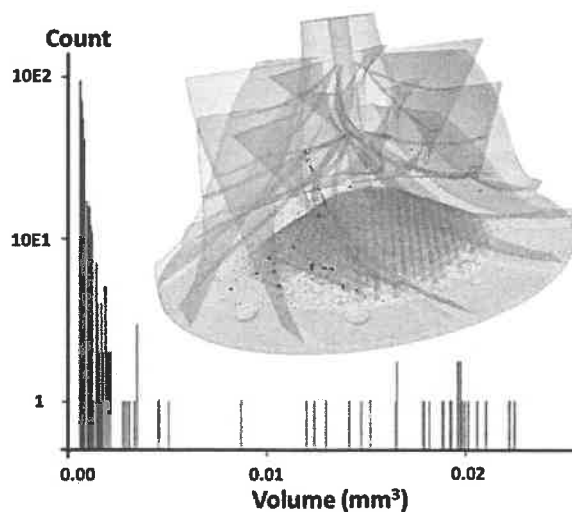


Figure 9. Porosity distribution for the LPBF AM compressor wheel. Colors on the 3D model correspond to the color-code of the x-axis.

The void analysis is limited by the spatial resolution of image data, which is at the same time limited by the voxel size of CT scan. Thus, pores with a diameter on the order of one voxel or less cannot be detected or differentiated from noise in the CT image. In the present work, the AM cooling water manifold was scanned with around a $63 \mu\text{m}$ voxel size while the compressor wheel was scanned with a $42 \mu\text{m}$ voxel size.

Developers of Volume Graphics software [8] provide recommendations for differentiating noise from defects as follows: for a pore to be confidently differentiated from noise, it should have at least 2 voxels in diameter or roughly 8 voxels in volume. This means that given the voxel sizes used for CT scan in this research, the present analysis can only distinguish voids with volumes larger than $(2 \times \text{voxel size} = 0.126 \text{ mm})^3 = 0.002 \text{ mm}^3$ for the AM cooling water manifold, and voids with volumes larger than $(2 \times \text{voxel size} = 0.084 \text{ mm})^3 = 0.0006 \text{ mm}^3$ for the AM compressor wheel. In order to assess smaller voids or porosity defects, new CT scans can be performed at higher resolution, or regions of interest in the object can be scanned. This can be achieved by putting the object closer to the X-ray source than in a typical cone-beam CT scanning setup.

CONCLUSIONS

For safety-critical components, it is essential that parts are created that satisfy design allowables so that parts can be certified/qualified for use. As part of this process, it is important to know whether there are voids and/or inclusions present inside the part, how large they are (both individually and in total), and where they are located, as reviewed recently [9]–[12]. In addition, dimensional tolerances of the AM part must conform to those of the original design, while the surface roughness of as-deposited parts may affect the structural and/or functional performance of the part, depending on the application, as reviewed recently [11]. In general, CT enables nondestructive documentation of the following main features that could affect the structural/functional integrity of (internal structures in) AM parts:

- ✓ Powder residues blocking channels
- ✓ Departure from the CAD model – dimensional analysis, wall thickness measurements, etc.
- ✓ Defects (voids and inclusions) – porosity, contamination, cracking.

Using these guidelines, this study has shown the benefits of using X-ray CT for the assessment of AM parts. Two prototype parts with complex internal structures (i.e. compressor wheel, cooling water manifold) were manufactured by AM and subsequently analyzed using CT to document features that could affect the structural

and/or functional integrity. Micro-cracks and voids were detected on the inside of the cooling water manifold, while path closures were detected in the internal structure of the AM compressor wheel. These could affect the mechanical integrity depending on how the part is loaded. In addition, powder residues were evident in the CT images of the interior structures of the AM cooling water manifold. These could affect the functional performance of the part by restricting the flow of cooling water. Dimensional tolerances can also be checked with CT. In the present examples, non-destructive CT measurements of actual part dimensions were compared to reference CAD values. The AM parts exhibited variations in dimensions, with tolerances ranging from 0.02 mm to around ± 0.2 mm with respect to the nominal reference CAD geometry. The CT measurements in the present work enabled dimensional measurements to be made with uncertainties on the order of 10 micrometers. This uncertainty is much less than the measured variances in the AM parts. As such, the deviations from part-to-CAD analysis are predominantly related to the AM process rather than to uncertainties from the measurement process with X-ray CT.

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TOWARDS AN ADDITIVE SURFACE ATLAS

Adam Thompson¹, Nicola Senin^{1,2}, Richard K. Leach¹

¹Manufacturing Metrology Team, University of Nottingham, NG7 2RD, UK

²Department of Engineering, University of Perugia, 06125, Italy

INTRODUCTION

There is little doubt that additive manufacturing (AM) will have a profound effect in many industries, and there are countless examples of polymer products. But, if AM is to be used in earnest in high-value, advanced manufacturing, for example, in the aerospace or medical industries, then it will be metals and ceramics that will be the game-changers. However, right now, the integrity of metal or ceramic parts essentially made with powder bed fusion AM processes, is not equivalent to that expected from more conventional manufacturing techniques (casting, forming, machining). AM parts made from metal powders tend to have high surface roughness values and can suffer from undesired material characteristics (e.g., high porosity or large numbers of defects). Also, where one would not dream of manufacturing a part with subtractive techniques without a dimensional tolerance scheme, it is still not clear exactly how to apply tolerance principles to AM parts [1]. AM does not currently have the benefit of the over one hundred years of research into the production of components that is the hallmark of precision subtractive techniques [2].

From the metrology standpoint, AM should be no different to conventional manufacturing. In fact, we would argue, that a lack of metrology in current AM machines and processes is hindering the commercialisation of the resulting products. Whilst the form of an AM object is critical, it is often the surface texture that has the biggest impact on the object's functionality. Surface texture is the fine-scale geometry and is often the limiting factor when considering the tolerance of an AM part. Whereas surface texture height structures can be produced on the nanometre scale using precision subtractive technologies, due to the nature of powder-based AM techniques, surface texture height structures of tens of micrometres are more normal [3, 4]. This throws up a number of metrology questions, some of which include:

(i) Can we use conventional surface texture instruments to measure AM surfaces – high slope angles and undercuts, resulting in multiple reflections and shadowing, causing problems for

optical instruments? (ii) Can we use conventional filtering methods and texture parameters with AM surfaces? (iii) Can we examine the surface texture of an AM part to elucidate how the surface was manufactured – AM processes involve some highly complex physics, so this involves a significant amount of experimental and theoretical research? (iv) How can we measure surface texture in-line?

Before answering these questions, it is necessary to understand what is actually present at the surface of an AM part. To this end, we are embarking on a comprehensive measurement and analysis campaign that will result in an atlas of AM surfaces at many different scales of observation. For this campaign, we are using a host of instrument types: contact, optical and scanning electron microscopy (SEM). This paper will present some preliminary results from this campaign – the work is in progress, but some conclusions can already be drawn.

METHODOLOGY

In order to begin building the atlas, a Ti6Al4V, cube-shaped test artefact of size (20×20×20) mm was generated using selective laser melting (SLM) [5]. Measurements were performed on a single portion of the top surface (i.e. the last layer deposited in the AM process). The cube was produced with a Renishaw AM250 SLM machine, using processing parameters for Ti6Al4V as provided by the machine manufacturer. It should be noted that due to the nature of the SLM process, significantly different topographies are typically observed on the top, side and bottom surfaces [3]. The top surface was chosen for this initial study as the most representative of the physical phenomena involved in layer generation [3], but work is in progress to also characterise the side and bottom surfaces. The portion of the surface chosen for measurement (region of interest – ROI) was approximately a (2×2) mm corner region; the corner was chosen so that visible edges could be used to align multiple measurements for comparison purposes. The chosen ROI was visually inspected to ensure

that it was representative of the surface as a whole.

The following technologies and instruments were used to acquire topography data:

- FV: focus variation (Alicona Infinite Focus G5), with multiple objectives and lighting conditions;
- FS: focus stacking (Keyence VHX-5000) with 100× to 1000× objective and coaxial lighting;
- CSI: coherence scanning interferometry (Bruker Contour GT) with multiple objectives.

Note that FV and CSI are supported by ISO specification standards ([6] and [7] respectively), while FS is a term used in this work to refer to a different implementation of the same focus-finding principle as FV, i.e. identification of in-focus points by contrast detection on images. Given the significant importance of software processing in these technologies, differences between implementations can be dramatic.

In addition, conventional optical microscopy (Nikon Eclipse LV100, using 5×, 10×, 20×, 50× and 100× objectives with coaxial light) and SEM (Philips XL30, at 61× magnification, in secondary electron mode) was used to acquire orthophotos of the ROI.

Details on the measurement set-ups

Focus-based technologies (FV and FS) are highly dependent on surface appearance to identify conditions of maximum local contrast, essential to determine the distance of each measured point from the focal plane. Focus-based technologies are, therefore, significantly influenced by lighting conditions [8]. For FV, multiple lighting conditions were investigated, consisting of combinations of coaxial, polarised and ring light with different intensities. With FS, it was only possible to test coaxial light, albeit at different intensities. The following objective lenses were used with FV: 5× (NA 0.15, FoV 2.82 mm × 2.82 mm, lateral resolution 7 μ m), 10× (NA 0.30, FoV 1.62 mm × 1.62 mm, LR 4 μ m), 20× (NA 0.40, FoV 0.81 mm × 0.81 mm, LR 3 μ m) and 50× (NA 0.60, FoV 0.32 mm × 0.32 mm, LR 1.5 μ m), where LR is lateral resolution. Topography datasets were acquired using a single field of view at 5×, and multiple, stitched fields of view at 10×, 20× and 50× (stitching done in the Alicona software). Two additional magnifications, 2.5× and 100×, were considered, but ultimately discarded; the former being too low to capture relevant topographic details, the latter being too time consuming to

achieve equivalent lateral coverage, and resulting in too large datasets. Due to limited availability, only the 100× to 1000× variable objective at 200× was used with FS (FoV 3.05 mm × 2.28 mm); coaxial lighting was manually tuned to achieve the best possible result by visual inspection. When using FV and FS both topography data (height maps) and colour data (colour maps) of the ROI were obtained.

CSI measurements were taken using 2.5× (NA 0.07, FoV 2.5 mm × 1.9 mm), 5× (NA 0.12, FoV 1.3 mm × 1.0 mm) and 20× (NA 0.4, FoV 0.3 mm × 0.2 mm) objective lenses; initially considering only a single FoV. The intention was to verify the actual feasibility of acquiring rough topography with CSI technology, before attempting to cover larger portions of the surface. From CSI measurements, only topography data (height maps) were obtained.

SEM and optical images were taken with the purpose of achieving a comprehensive visual investigation of the topography. For optical imaging, lighting conditions were set to achieve the best possible visual result; however, due to poor depth of field at higher magnifications, optical images were discarded in favour of the higher quality output of the focus-stacked images from both the FV and the FS microscopes.

The raw datasets acquired from each instrument were analysed in the topography analysis software DigitalSurf MountainsMap. The datasets were levelled by least-squares mean plane subtraction. Alignment of areal topography data from FV and FS measurements was performed by using dedicated functions in the software and manual refinement via visual inspection. Topographic formations at the cube edges and other visible landmarks were used to perform alignment. CSI datasets were not aligned given their low quality, owing to an excess of measurement artefacts and non-measured points. SEM image data was also overlaid to the areal topography datasets, by means of manually aligning visually identified landmark correspondences, within the software.

The purpose of the alignment procedure was to investigate how each notable topographic feature located within the ROI would be captured if measured with different technologies and measurement set-ups. At this stage of the

research, the investigation was purely qualitative and based on visual comparison of the results, rather than on the computation of some texture parameter or other quantitative descriptor. The following notable topographic features were targeted, as summarised in Figure 1. *Weld tracks*: directly resulting from the interaction of the laser with the powder bed, along the traversal path, during layer generation; *weld track ripples*: higher-frequency, semi-periodic features appearing on the weld track, as a result of the melt pool formation process; *balling and spatter*: localised, protruding features, sometimes similar to spheres, classifiable either as balling or as spatter depending on size and conformation of surroundings; *pores*: small recesses, sometimes showing portions of the layer underneath, typically due to incomplete welds [9-11]. These notable topographic formations carry significant measurement challenges: high slopes, undercuts and step-like transitions are often featured, as well as significant changes of optical properties within the field of view, e.g. alternation of highly reflective and opaque regions, alternation of more varied and more uniform colour patterns.

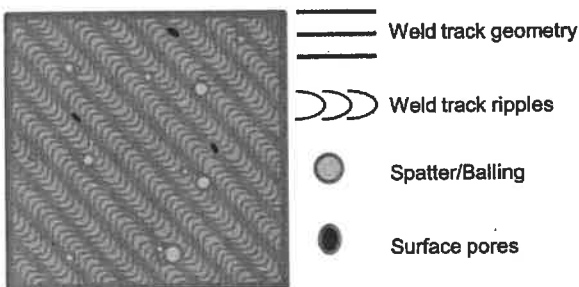


Figure 1. Schematic diagram displaying a top view of features found on a typical SLM top surface.

Within the MountainsMap software, visual comparisons were performed on the *xy* (image) plane, i.e. by observing the aligned topographies from above, but also on cross-sections, i.e. by looking at aligned topography slices from the side. In cross-section view, only height data was investigated; however, on the image plane, both height maps and colour maps were investigated.

RESULTS

Visual inspection of colour maps

Colour maps are a powerful tool for gathering qualitative information about surface appearance and the shape and layout of its most relevant features. For optical instruments, the downside is that surface appearance is evidently related to a combination of the optical properties of the surface and the type of incident illumination. The same surface can look considerably different if imaged through coaxial light, polarised light and/or ring light, colour wavelength plays also a relevant role. Analogously, different set-ups at the image detector will determine the amount of saturation, contrast, etc., which can make colour maps appear different. Similar considerations apply to non-optical imaging, more specifically to SEM, in this case pertaining to electron beam energy and sensitivity parameters at the detector. In Figure 2, the ROI is shown as it appears in the colour maps generated from FV, FS and SEM (in grayscale) measurements. Differences between FV and FS should be attributed mostly to different illumination conditions and optics, and not to the measurement technology (FS vs. FV). At first glance, it is evident how light plays a fundamental role in highlighting the higher frequency details in the FS and FV images (e.g. weld track ripples); saturation and reflection effects are greatly reduced on the SEM image.

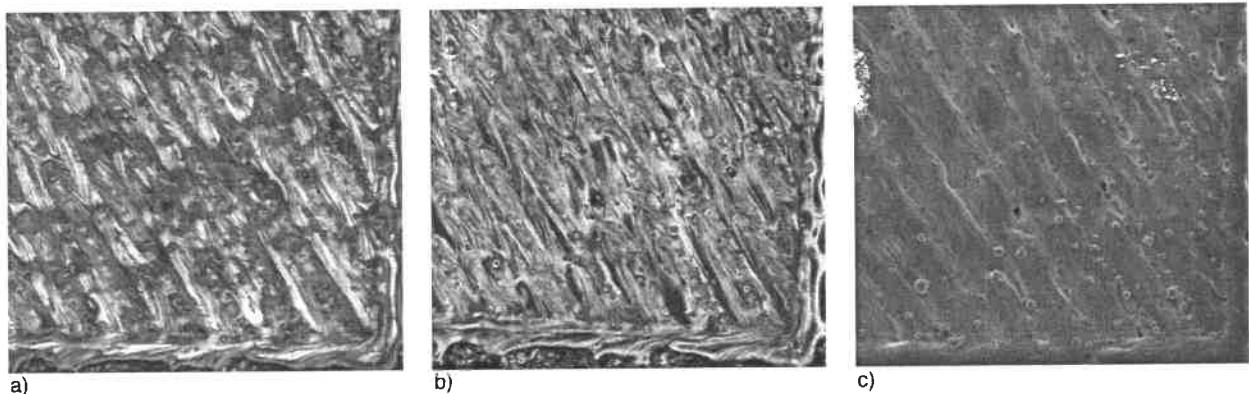


Figure 2. Colour maps (2 mm × 2 mm): a) FS 500× magnification, coaxial light, multiple stitched fields of view; b) FV 20× magnification, ring light, multiple stitched fields of view; c) SEM, 61× magnification.

Visual inspection of height maps

Concerning height maps, the first notable result is the poor quality of CSI data. Figure 3 refers to one of the most successful measurements, obtained with 20 $\times$ magnification, highlighting how the technology is capable of capturing some high frequency components (weld track ripples) but fundamentally fails at capturing most of the highly irregular topographic features (e.g. weld tracks). Further investigation of CSI capability to acquire SLM topographies is needed, but it is suspected that the high slope angles are causing significant image artefacts [12]. Amongst focus-based technologies, FS showed poorer performance than FV, consistent with the different nature and purpose of the Alicona and Keyence microscopes. The importance of lighting conditions in determining FV performance at a given magnification is highlighted in Figure 4 (and discussed in detail in [8]). Ring light appears to provide the better conditions for reconstructing the topography (e.g. less visible noise, clearer depiction of localised features), presumably due to ring light better supporting FV with contrast detection.

As with most optical technologies, in FV an increase in magnification allows the capture of finer detail (higher frequency features). In Figure 5 it can be seen how the weld track ripples become increasingly more visible at higher magnifications. Somewhat less evident is higher magnification being better capable of capturing more difficult regions (e.g. higher slopes). The price to pay with higher magnification is an increase of measuring time and difficulty, as stitching is increasingly needed to cover the same area. Quantitative analyses should be used to determine to what extent stitching may

alter topographic content. On the other hand, the cross-section profiles in Figure 6 show that in FV, magnification can be kept low, while still capturing many of the salient traits at lower frequency (e.g. profile of the weld tracks).

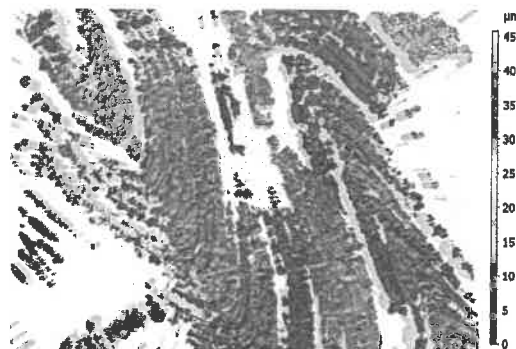


Figure 3. Height map obtained with CSI, 20 $\times$ magnification (0.24 mm $\times$ 0.3 mm).

Reconstruction of localised features

Finally, it is interesting to see how fidelity in reconstructing localised topographic features is altered with measurement technology, magnification and set-up. In Figure 7, small formations due to balling/spatter are visible, together with a small number of pores. The same protruded features may appear more or less round, larger or smaller, symmetric or asymmetric depending on measurement technology; and the pore may be misinterpreted as a protruded feature with some technologies [12]. These results suggest that caution should be advised when visually inspecting topography measurement results.

DISCUSSION

The current results already provide a preliminary idea of the topography of an SLM surface when

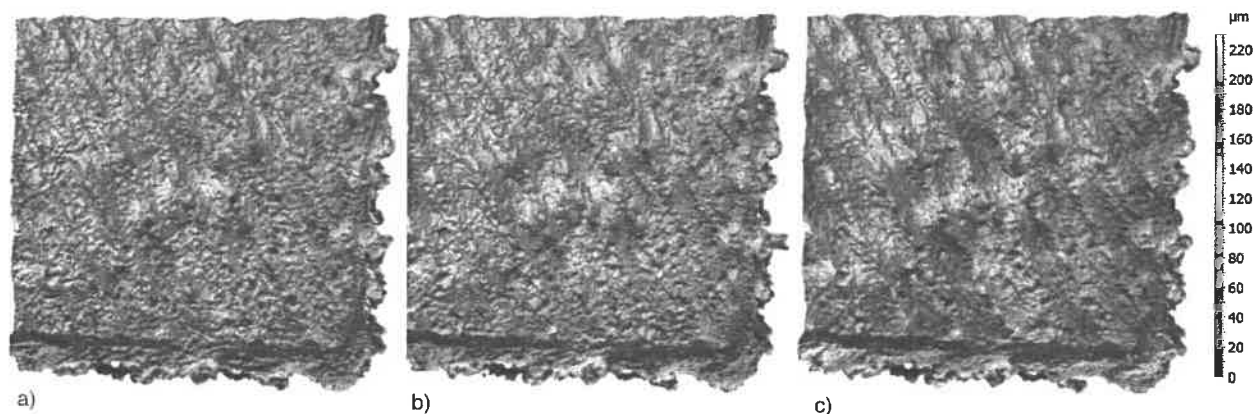


Figure 4. Height maps from FV (2 mm $\times$ 2 mm); a) 5 $\times$ magnification, coaxial light; b) 5 $\times$ magnification, polarised coaxial light; c) 5 $\times$ magnification, ring light.

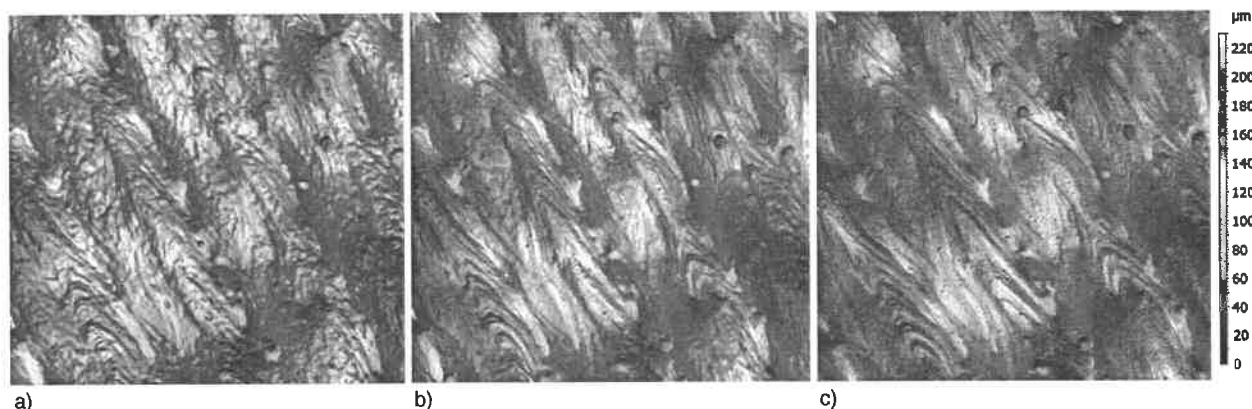


Figure 5. Height maps from FV (0.8 mm × 0.8 mm); a) 10× magnification, ring light; b) 20× magnification, ring light; b) 50× magnification, ring light

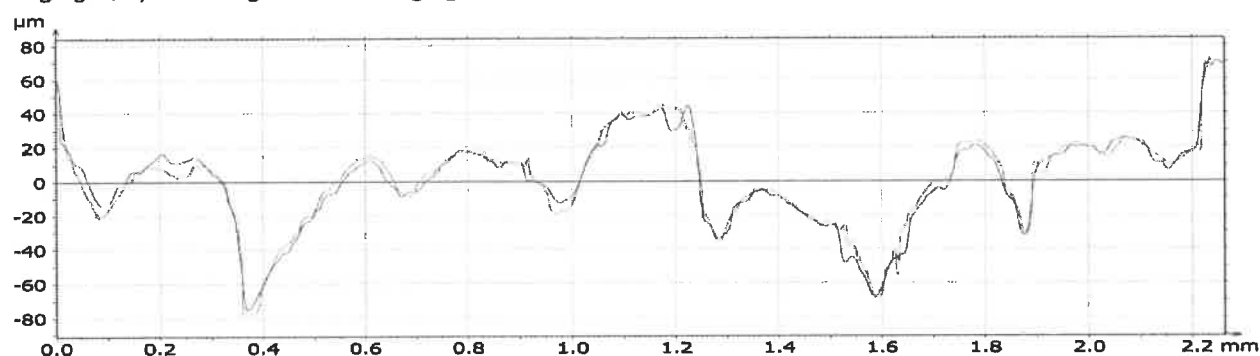


Figure 6. Aligned cross section profiles from FV data: red - 5× magnification, ring light; green - 10× magnification, ring light; blue - 20× magnification, ring light



Figure 7. Details of height maps and colour maps (0.3 mm × 0.3 mm) showing localised features (spatter, balling, pores) a) FS 500x magnification, coaxial light; b) FV 50x, ring light and c) SEM 61x magnification.

measured with some of the most common, mainstream technologies. However, the measurement campaign is still in progress, with plans to include atomic force microscopy (for observing at smaller scales), confocal and point-autofocus microscopy, and X-ray computed tomography (to overcome limitations with high slopes and undercuts). A more complete investigation should not only include more measurement technologies, but also a more quantitative and robust way to compare results: research is in progress to optimise the dataset

alignment process and to quantify local and global topographic differences in multi-sensor scenarios. This includes, e.g., bandwidth matching, i.e. the process of identifying the correct ranges of spatial frequencies shared by multiple measurement technologies [13]. In addition, a proper quantitative comparison implies the execution of measurement repetitions, and the statistical treatment of results, as well as the incorporation of measurement and manufacturing process uncertainties.

Despite the above considerations, a few interesting conclusions can be drawn from the available data: a) when an opinion needs to be reached about the topography of a SLM surface, it is intrinsically unadvisable to rely on any measurement result taken individually. Experimental findings demonstrate that no single technology/set-up is optimal in respect to the notable features that need investigation; 2) no measurement technology/set-up amongst those compared can be considered "higher class" than the others and thus act as reference; in other words, there is no "truth" to rely upon at this stage; c) consistent output of multiple technologies and at multiple scales, i.e. agreement across technologies/set-ups in regards to a specific feature/topography detail, is likely a sound starting point for establishing feature-specific references, at least until a more theoretically sound validation, or a higher accuracy instrument, is available.

CONCLUSIONS AND FUTURE WORK

Some of the most popular mainstream measurement technologies were used to measure a region of interest on the top surface of a Ti6Al4V cube fabricated by SLM. Notable topographic formations were identified and their digital reconstructions in the different measurement configurations were compared via visual inspection. Qualitative results allow the identification of some key aspects in regards to agreement and disagreement of measurement results, as well as advantages and weaknesses specific to each measurement technology and configuration. Additional research work is needed to complete the experimental campaign by adding more measurement technologies, and to provide a more theoretically sound and quantitative approach to the comparison. Future work includes also the extension to different types of surfaces, materials and AM processes.

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AREAL SURFACE TEXTURE PARAMETERS ON SURFACE

L. Pagani¹, P.J. Scott¹

¹EPSRC Centre for Innovative Manufacturing in Advance Metrology,
Centre for Precision Technologies (CPT),
School of Computing and Engineering,
University of Huddersfield, Huddersfield, HD13DH, UK

INTRODUCTION

Additive manufacturing (AM) techniques enable the manufacture of components with free-form geometries and complex internal and external features. X-ray computed tomography (CT) is increasingly being used to inspect internal features of AM parts. An advantage of the CT process, compared to optical and stylus instruments with limited acquisition slope angles, is the ability to reconstruct reentrant features (undercuts). Processing reentrant features provides an advantage in the computation of surface parameters. If the surface includes many reentrant features, their elimination can lead to a biased estimation of parameters related to the height or the area of the scale limited surface. A unified framework capable of handling free-form surfaces, with generic form surface, reentrant features and unevenly spaced points, such as those from CT reconstruction, will be proposed. Standard software instruments employed for roughness parameter require evaluation of height data on a rectangular grid. This allows the computation of areal parameters based on discrete methods with good approximation, dependent upon the sample size. The reconstruction from CT volume to mesh allows performance of an adaptive meshing based on the maximum allowable distance between the implicit function (implicit surface defined by a constant grey value) and the final triangular mesh [1]. With irregular meshes it is not possible to perform the integral with the discrete approximation and a bias on the parameters computation can arise. In this paper an approach that approximates a generic mesh based on locally refined (LR) B-spline is proposed [2]. The approach can be applied to a generic form surface because the local stretching of the surface is taken into account. Mesh parameterisation enables to handle undercuts, each acquired point is described as a function of two abstract parameters. In this paper the proposed method will be compared with the discrete (ISO 25178-2 compliant [3]) method implemented in standard software packages [4]. Since filtering techniques based on a general mesh are

not yet defined in the standard, the primary surfaces, the surface after removing the form, will be analysed. The areal parameters of a Rubert sample (casting plate 334, nominal Ra of 25 μm) measured with a focus variation (FV) instrument will be evaluated. Two form surfaces will be taken into account: plane and cylinder. Robustness of the discrete method will be finally evaluated with the mesh reconstructed from two CT measurements: the Rubert sample and an AM part.

PARAMETER COMPUTATION

In this paper it is assumed that a manufactured surface can be described with a regular parametric surface $\Sigma \subset \mathbb{R}^3$ as

$$\mathbf{r}(u, v) = \begin{cases} x = x(u, v) \\ y = y(u, v) \\ z = z(u, v) \end{cases} \quad (1)$$

with $\mathbf{u} = (u, v)^T$ and $U \subset \mathbb{R}^2$. U is called the parameters space and it is usually described with a square of unitary edge. Suppose that it is possible to decompose the surface in two parts

$$\mathbf{r}(u, v) = \mathbf{r}_{form}(u, v) + \mathbf{r}_{res}(u, v) \quad (2)$$

where $\Sigma_{form} : \mathbf{r}_{form}(u, v)$ represents the form and $\Sigma_{res} : \mathbf{r}_{res}(u, v)$ the residual surface. If a total least squares approach is implemented the last term can be rewritten as

$$\mathbf{r}_{res}(u, v) = r_{res}(u, v) \mathbf{n}(u, v) \quad (3)$$

where $r_{res}(u, v)$ is the distance between $\mathbf{r}(u, v)$ and its projection on the form surface $\mathbf{r}_{form}(u, v)$ and $\mathbf{n}(u, v)$ is the surface normal. $r_{res}(u, v)$ can be interpreted as a scalar field on the surface $\mathbf{r}_{form}(u, v)$. If it is possible to describe the value of the surface $r_{res}(u, v)$ on the form surface without stretching and if no reentrant features appear on the residual surface, the parameters can be computed with the definition of the ISO 25178-2 norm [3]. When the form surface cannot be described by a developable surface, but it is a general free-form surface, the local stretching must

be taken into account [5]. Form surfaces developable to a plane are all the surfaces where the gaussian curvature is null everywhere [6], such as cylinder. Let $r_{form,i}$ the partial derivative along the dimension i , the parameters on the primary surface can be computed weighting the "height" values with the infinitesimal surface area

$$d\sigma_{form} = \|r_{form,u}(u, v) \times r_{form,v}(u, v)\| du dv.$$

According to the previous definition the arithmetic mean of the absolute value of the height can be computed as

$$Sa = \frac{1}{A} \iint_{\Sigma_{form}} |r_{res}(u, v)| d\sigma_{form} \quad (4)$$

where A is the area of the form surface, the root mean square error as

$$Sq = \sqrt{\frac{1}{A} \iint_{\Sigma_{form}} r_{res}^2(u, v) d\sigma_{form}} \quad (5)$$

the skewness as

$$Ssk = \frac{1}{A Sq^3} \iint_{\Sigma_{form}} r_{res}^3(u, v) d\sigma_{form} \quad (6)$$

and the kurtosis as

$$Sku = \frac{1}{A Sq^4} \iint_{\Sigma_{form}} r_{res}^4(u, v) d\sigma_{form}. \quad (7)$$

SURFACE APPROXIMATION

In order to estimate the parameter of the LR B-spline, a parameterisation of the reconstructed mesh is firstly computed. Stretch minimising approach proposed in Yoshizawa et al. [7, 8] will be employed because it minimise the area distortion, it is therefore a good candidate for the surface reconstruction. This parameterisation will be used as a common parameterisation for all the surfaces involved. The form surface is then estimated with a total least squares (TLS) approach. Plane and cylinder form surfaces will be analysed, but the proposed method does not depend on a specific form surface. The differences between the point cloud and the projections on the form surface are firstly computed. Both the two point clouds, form and residuals, are then approximated with the LR algorithm. The height areal parameters (Sa , Sq , Ssk and Sku) of the primary surface can be computed as the integral of a scalar field, represented by the residuals, on the form surface. Since both the involved surfaces, r_{form} and r_{res} , share the parameters domain, the integration can

be performed with a numerical quadrature rule. The numerical integration is performed with the h-cubature method implemented in Johnson [9]. This method recursively partition the integration domain into smaller sub-domains, the quadrature rule is applied to each, until a convergence criterion is reach.

EXPERIMENTAL RESULTS

Parameters' computation with the proposed method will be compared with the discrete method implemented in standard software packages. Two surfaces were measured: a Rubert sample with nominal Ra equal to $25 \mu m$ and an AM manufactured part. The Rubert plate was measured both with a focus variation (FV) instrument and with a CT device, while only the CT data of the AM part will be analysed. The FV dataset will be firstly considered to verify the error of the surface approximation. The primary surface will be added to a portion of cylinder to evaluate the stability of the proposed method with a developable form surface. CT sets of data will be finally analysed to investigate the effect of an unequally points spacing on the computation of the parameters with a discrete method.

Rubert sample: FV reconstruction

A Rubert sample with nominal Ra of $25 \mu m$ was measured with the Alicona Infinite focus microscope [10]. Figure 1 shows a portion of the measured points of the Rubert plate. The form surface was approximated with the total least square plane, that corresponds to the first two scores of the principal component analysis (PCA) of the point cloud covariance matrix. To describe both

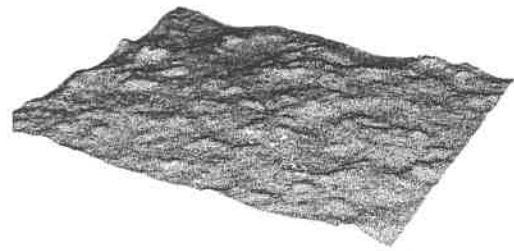


FIGURE 1. Point cloud of the nominal $Ra 25 \mu m$ plate

the form surface and the residuals (distance between the acquired point and its projection on the form surface) the LR B-spline algorithm was applied. A maximum value of 10 iterations and a threshold value of 0.01 were set in the approximation algorithm. During the approximation stage all the values were coded between 0 and 1 to

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	27.04	-	34.21	-	-0.33	-	2.93	-
ISO	27.04	0.01	34.21	0.02	-0.33	0.01	2.93	0.01
Surface	26.91	0.00	34.03	0.00	-0.31	0.01	2.93	0.01

TABLE 1. Height parameters FV data subset

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	31.67	-	40.66	-	-0.45	-	3.52	-
ISO	31.65	0.00	40.65	0.02	-0.45	0.01	3.52	0.01
Surface	31.61	0.00	40.54	0.02	-0.42	0.01	3.50	0.01

TABLE 2. Height parameters FV data

avoid the scale effect. The abstract parameterisation domain was $[0, 1]^2$. Since no undercuts were present in the FV mesh, it is possible to approximate also the scores of the PCA with LR spline method. In Table 1 are reported the parameters computed according to the ISO 25178-2 norm and with the proposed method. Error represents the estimated error of the numerical integration. The ISO parameters are computed both with the discrete method and the surface that approximate the scores of the PCA (ISO discrete and ISO). Surface represents the parameters computed with the proposed method. There is no difference between the discrete and the integral method. Due to the surfaces approximations the error between the proposed and the ISO method is larger, the differences are $0.13 \mu\text{m}$, $0.18 \mu\text{m}$ and 0.02 , respectively, for Sa, Sq and Ssk; there is no differences on the estimation of Sku. The above procedure was applied to the whole set of data of the measured Rubert sample. The evaluation of the parameters was applied to a bigger point cloud to check the robustness of the approximation. Table 2 shows the parameters computed on the primary surface. There is a small difference between the discrete and the splines based computation of Sa and Sq. The absolute values are 0.01 and $0.02 \mu\text{m}$. This errors are negligible compared to the values of the parameters. The differences between the surface and the ISO parameters get closer, they are $0.04 \mu\text{m}$, $0.11 \mu\text{m}$, 0.03 and 0.02 , respectively, for Sa, Sq, Ssk and Sku. In this section it has been shown that, although there is an error due to the surface approximation, the proposed method can be used to compute the areal height parameters (the max-

imum percentage differences are 0.4% for Sa and 0.5% for Sq).

Rubert sample: primary surface on cylinder

To check the stability of the proposed method a data set with a cylindrical form is analysed. The scores of the PCA of the previous test case were approximated with the MBA algorithm [11] to predict the points in a regular grid. The LR algorithm was not applied to investigate the robustness of the reconstruction method. The approximate points on a regular grid of 985×799 were then added, along the normal direction, to a portion of a cylinder. The angle of the cylinder ranges from $-\pi$ to 0 , while the radius is computed as

$$\rho = \frac{\Delta y}{\Delta \vartheta}$$

where Δy is the resolution of the coordinate in radial direction and $\Delta \vartheta$ is the angle resolution. With this radius the distances on the cylinder coincide with the distances on the plane. Figure 2 shows the simulated point cloud. The surfaces were reconstructed with the method described in the previous section. The computed parameters are reported in Table 3. The values of Sa and Sq slightly change, while Ssk and Sku have the same values. The differences between the parameters computed with the ISO compliant methods are negligible. The discrepancies between the methods based on the numerical integration are $0.10 \mu\text{m}$ for Sa, $0.13 \mu\text{m}$ for Sq and 0.02 for Ssk, illustrative that the proposed method can achieve good performance.

In order to evaluate the robustness of the procedure if the nominal form is not a plane, the whole

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	27.02	-	34.19	-	-0.33	-	2.93	-
ISO	27.01	0.00	34.17	0.02	-0.33	0.01	2.93	0.01
Surface	26.91	0.00	34.04	0.00	-0.31	0.01	2.93	0.01

TABLE 3. Height parameters FV data subset on cylindrical shape

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	31.31	-	40.26	-	-0.48	-	3.57	-
ISO	31.28	0.00	40.23	0.01	-0.49	0.01	3.58	0.01
Surface	31.18	0.00	40.06	0.00	-0.45	0.01	3.55	0.01

TABLE 4. Height parameters FV data on cylindrical shape



FIGURE 2. Point cloud on a cylindrical shape

Alicona point cloud was added to the half cylinder shape. Table 4 shows the computed height parameters. It is possible to observe that the differences are similar to the values of Table 3. In this section it has been shown that with the proposed method is possible to compute the height parameters approximating the form and the surface of residuals with the LR B-spline algorithm.

Rubert sample: CT reconstruction

Rubert sample with a nominal Ra of $25\ \mu\text{m}$ was acquired also using a Nikon XT H 225 microfocus CT. Nikon CT-Pro software [12] was used to perform the volume reconstruction. CT voxel size for all coordinates was $12.9\ \mu\text{m}$ (x, y, z). Mesh reconstruction was performed by an adaptive algorithm implemented in CGAL [1, 13]. This algorithm allows to reconstruct an implicit surface with a desired approximation; the maximum allowable error was set to $5\ \mu\text{m}$, almost $\frac{1}{3}$ of the voxel size. The output mesh is a manifold mesh,

so no post processing is needed in order to compute the parameterisation. It should be noted that the mesh reconstructed with the marching cube algorithm [14] may have some non manifold vertices or edges. Figure 3 shows a subset of the reconstructed point cloud. Two datasets will be analysed, a subset and the whole point cloud. These sets of data correspond to the meshes analysed in the previous section.

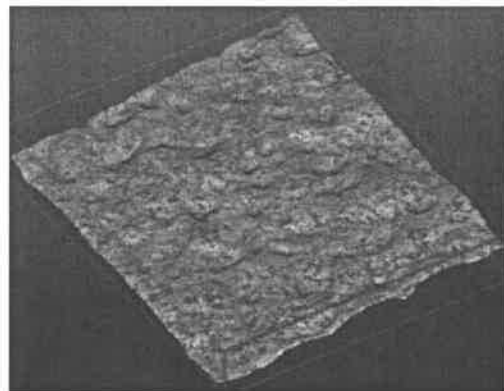


FIGURE 3. Subset of the whole point cloud

Considering the applied adaptive meshing the spacing of the points is not constant, this can lead to a biased estimation of the height parameters with the ISO discrete method. Since the surface may presents some undercuts, it is not possible to approximate the surface of the scores of the PCA. It should also be noted that the method called ISO discrete is not compliant with the ISO 25178-2 because it is not an approximation of integrals described in the standard. The values will be computed to evaluate the bias. After applying the parameterisation and the reconstruction

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	30.26	-	38.58	-	-0.02	-	3.01	-
Surface	31.62	0.00	39.94	0.01	-0.51	0.01	2.33	0.01

TABLE 5. Height parameters CT data subset

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	35.22	-	44.59	-	-0.20	-	3.19	-
Surface	36.35	0.00	46.03	0.05	-0.61	0.01	3.24	0.01

TABLE 6. Height parameters CT data

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	16.37	-	20.61	-	-0.41	-	3.43	-
Surface	15.07	0.01	19.09	0.08	-0.31	0.01	3.65	0.01

TABLE 7. Height parameters AM part

the areal parameters were computed. Tables 5 and 6 show height parameters of the small and the big dataset. The difference between the ISO (discrete) and the surface method increase compared to the previous test case. This is the effect of the unevenly spaced points and the reentering features. The discrepancies are 1.36 and 1.13 μm for Sa, 1.36 and 1.44 μm for Sq, 0.49 and 0.41 for Ssk and 0.68 and 0.05 for Sku.

AM part: CT reconstruction

An additive manufactured part was measured and the surface was reconstructed with the algorithm mentioned above. CT voxel resolution was 17.5 μm in x , y and z directions. The threshold was selected according to the ISO 50 method implemented in VGStudio Max software [15]. A magnification, where it is possible to observe a reconstructed undercut, is shown in Figure 4. Reconstructed surface was again parameterised and reconstructed with the LR B-spline approximation. The computed parameters are reported in Table 7. Sa and Sq parameters computed with the discrete approximation are biased, while the differences between Ssk and Sku are negligible. The absolute value of the difference is comparable to the previous test case. But, since the estimation are smaller, the percentage differences correspond to 8.62% and 7.96% for Sa and Sq. These discrepancies should be taken into account because the values are computed on the same set

of data.

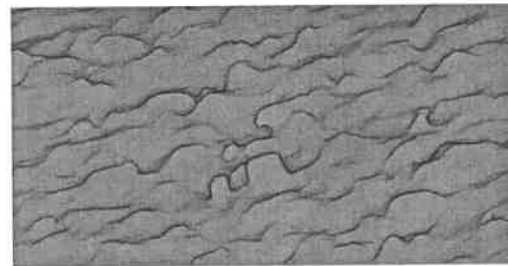


FIGURE 4. Undercuts on the reconstructed surface

CONCLUSION

A method to reconstruct and compute the areal height parameters has been proposed. Parameters values have been compared with the ISO 25178-2 definition on a point cloud measured with a focus variation device. It has been shown that the parameters computation with the proposed method is robust respect to the form surfaces analysed: plane and cylinder. The robustness of the ISO parameters based on the reconstruction of two CT measurements has been verified. The computation of the Sa and Sq parameters with the discrete approximation is biased, while the differences of the estimation of Ssk and Sku are negligible. Although the standard method implemented in common software packages is slightly biased, when the surface has some undercuts it

is not possible to compute other parameters or apply a filter (smoothing) on the point cloud. The proximity information is lost, neighbours points in the geometric space (x , y and z) can be far along the surface. The present work has presented a method to compute height parameters on a general free-form surface. Future developments involve the definition of other areal parameters if the analysed surface has a free-form shape or present undercuts. The concept of scale limited surface has also to be defined and investigated; all the computed values in this paper refers to the primary surface because the S and L operators are defined only if the measured point are on a regular grid.

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PRELIMINARY STUDY TOWARD SURFACE TEXTURE AS A PROCESS SIGNATURE IN LASER POWDER BED FUSION ADDITIVE MANUFACTURING

Jason C. Fox¹, Shawn P. Moylan¹, and Brandon M. Lane¹

¹Intelligent Systems Division

National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

Additive manufacturing (AM) allows for highly complex designs that cannot be achieved through subtractive or formative manufacturing techniques. A limiting factor of AM, however, is the as-built surface quality. Additionally, there is limited knowledge on how specific surface features or defects translate to measured surface parameters. If a strong quantitative understanding of the relationships between the processes that cause specific surface features and the measured surface parameters can be developed, then surface texture has the potential to be developed as a process signature. Vertical and upward-facing surfaces of varying angles and process parameters were built and analyzed. Analysis of Ra was found to provide little information on the specific features that make up the surface texture. RSm and Rc , however, can indicate a shift between surfaces dominated by partially melted powder particles and ones dominated by material from the re-solidified melt track, which was also seen for downward-facing surfaces in prior work. The correlations presented are a step toward developing surface texture as a process signature for AM.

INTRODUCTION

Additive manufacturing (AM) has emerged as a key technology for production applications [1]. Laser powder bed fusion (L-PBF), a subset of AM, in particular has generated a great deal of interest. This is due to the fine focusing optics, layer thicknesses of 20 μm to 100 μm , and the powers and velocities over which the system operates allows for fine detail compared to other AM technologies [2].

Despite the advantages of AM, however, a limiting factor affecting widespread adoption is the as-built surface topography of finished parts. Methods exist to process surfaces *in situ* [3,4] or *ex situ* [5,6], but are limited, especially as design

complexity increases [7]. Thus, improvements in the as-built surface texture has been cited as a key need [8].

Optimization of surface roughness has been the focus of several studies in AM research. Craeghs *et al.* used optical sensors to control melting, resulting in a reduction in top and overhanging surface roughness [9]. Diatlov *et al.* performed a spectral analysis of the arithmetical mean roughness (Ra) for a wide range of surface slopes, finding a potential to determine surface characteristics [10]. Work by Abd-Elghany and Bourell investigated the effect of layer thickness on top and side surface roughness, finding that thick layers lead to increased surface roughness due to a tendency of the particles to form voids once removed during post processing [11]. Jamshidinia and Kovacevic found that an increase in surface roughness can occur due to increased heat accumulation causing an increase in partially melted powder particle attachment [12].

There is a wide range of mechanisms that contribute to the roughness of an AM surface, which include the process input parameters as well as the complex physical processes that occur during melting and solidification of the metal powder [13]. For example, Kleszczynski *et al.* found that there is a positional dependency on surface roughness [14], a factor commonly overlooked by the research community. Additionally, the majority of research cites Ra when determining surface roughness; however, this parameter tells us very little about the makeup of the surface. Some research has investigated additional parameters. For example, Triantaphyllou *et al.* found that the area skewness (Ssk) can be used to differentiate between upward- and downward-facing surfaces [15]. However, if surface texture is to be used as a process signature a strong quantitative understanding of the relationship

between the mechanisms that contribute to surface texture and measured surface parameters, including and not limited to R_a , must be investigated and understood.

Related work by the authors has shown the potential of using existing parameters beyond R_a to better understand the characteristics of a surface for downward-facing surfaces [16]. In this work, upward-facing and vertical surfaces of the parallelepipeds are analyzed. Qualitative and quantitative analyses show that relationships seen in the mean spacing of profile irregularities (RS_m) and the mean height of the profile elements (R_c) of downward-facing surfaces can also be seen in the vertical and upward-facing surfaces. These correlations point toward a direction for further research into relating surface finish metrics with the physics of the laser powder bed fusion process and the development of surface texture as a process signature.

EXPERIMENTAL PROCEDURE

The experiments focus on test parts that were built on a commercially available L-PBF system. The parts were designed as symmetrical parallelepipeds, having two parallel, vertical parallelogram faces; two rectangular faces; and two square faces. The acute angle of the parallelogram was varied, resulting in test parts with inclined/overhang angles (α) of 30°, 45°, 60°, and 75° as measured from the build plane. Figure 1 illustrates the test part with $\alpha=60^\circ$.

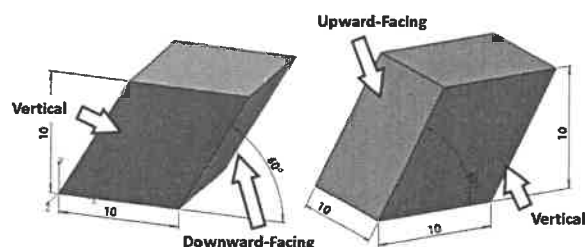


FIGURE 1. Model parallelepiped for surface characterization, where $\alpha=60^\circ$. Dimensions are in millimeters. Build direction is positive z .

The test parts were built on the EOS M270¹ system at the National Institute of Standards and

Technology (NIST). All parts were fabricated in the same build. Stainless steel powder (EOS GP1, which is chemically equivalent to U.S. classification 17-4 stainless steel) reclaimed from several previous builds was used. The powder was screened through an 80 μm sieve before the build. Since it is likely that the condition of the feedstock powder affects the surface texture of the resulting part, powder samples were taken and are currently being analyzed.

Prior work assessed the effect of process parameters on surface characteristics for downward-facing surfaces [16]. In that work, contour parameters with varying laser beam power and travel velocity were chosen in order to cover a wide range of the process space. It was found that two sets of parameters led to highly different surface characteristics. As such, the focus of this work will be on Characterizing the vertical and upward-facing surfaces from the two contour parameters sets shown in TABLE 1.

TABLE 1. Process parameters for experiments. Contour numbers are chosen to match designations from prior work [16].

Contour Number	Power (W)	Velocity (mm/s)	Line Energy – P/v (J/m)
4	40	700	57.1
9	195	700	278.6

A total of eight parallelepipeds were analyzed (i.e., two contour parameter sets with four values of α). As such, eight upward-facing surfaces and 16 vertical surfaces were analyzed (since each parallelepiped has two vertical surfaces). Test parts were positioned equidistant from the center of the build platform with the downward-facing surface of the parallelepiped forming a straight line to the center of the laser source. This was done to prevent as many of the positional dependency issues seen by Kleszczynski *et al.* [14] as possible. All surfaces were also at a slight angle (i.e., not parallel) to the recoater blade and that angle varies based on position on the build plate to maintain a constant angle relative to the laser. Additionally, the vertical surfaces are either facing towards the center of the plate (labeled Towards in later figures) or away from the center of the plate (labeled Away).

¹ Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

ANALYSIS METHODS

Surface characterization was performed using a white light interferometer, described in detail in [17], and 10x objective lens. Using white light interferometry to analyze a very rough surface is a challenge due to difficulty in achieving null fringe condition (perfect leveling of the sample surface being measured). Because of this, a diamond-turned aluminum disk was first used to level the sample platform prior to any measurements. Thus, the best leveling possible, assuming that the surface being measured and the surface laying on the platform are parallel, was achieved. This leveling procedure was performed before each measurement session to maintain a consistent leveling for each sample and prevent deviations due to errors caused by the leveling of the samples.

Seven images with 20 percent overlap were taken along each surface (perpendicular to the layers) and stitched together to create an approximately 5 mm long measurement. This created a large enough measurement of the sample surface to properly perform digital Gaussian filtering based on the ISO 4287 standard [18]. The values presented used a bandpass digital Gaussian filter with a short cut-off length of 25 μm and a long cut-off length of 0.8 mm. The filtering process results in an evaluation length equal to five long cut-off lengths, or 4 mm. These filters are defined by ISO 4287 and represent a common practice in AM surface roughness research [19].

Qualitative analysis using scanning electron microscopy was performed on selected surfaces.

RESULTS

Qualitative Analysis

Scanning electron microscope (SEM) images for two vertical surfaces can be seen in FIGURE 2. FIGURE 2a) shows a vertical surface built with set 4. In this image, the surface is dominated by partially melted powder particles, but the re-solidified material from the melt track as well as gaps in the melt surface can be seen.

FIGURE 2b) shows a vertical surface built with set 9. In this image, fewer partially melted particles are present and the surface is dominated by the re-solidified material from the melt track. Additionally, this combination of power and velocity led to material that was

damaged by the recoater blade on the downward-facing surface [16]. Similar damage can also be seen in this figure. A key difference between the vertical surface and the downward-facing surface, however, is the nature of the damaged material. These surfaces have a different orientation relative to the recoater blade because they form 90° angle when viewed from above. As such, the damaged material is scraped into the part from the vertical surface and out of the part from the downward-facing surface.

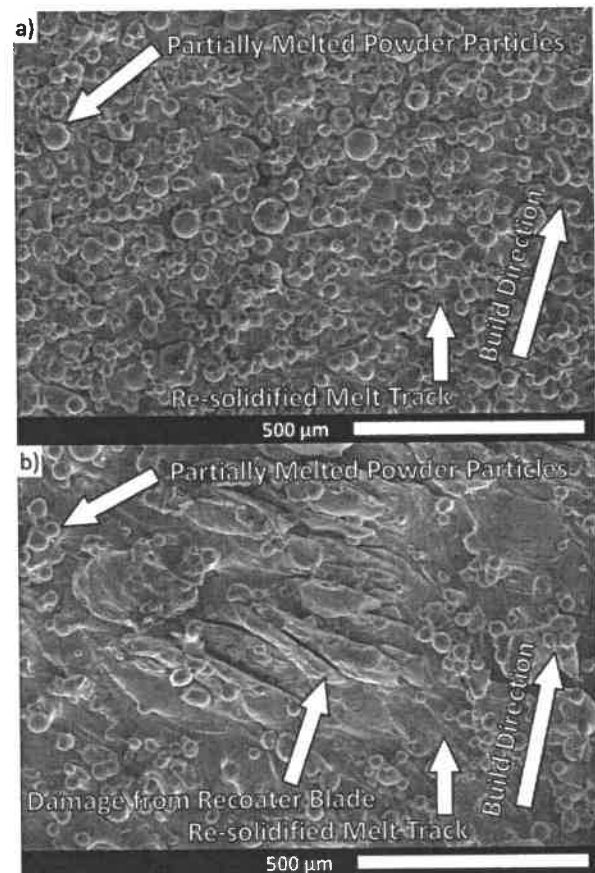


FIGURE 2. Vertical surfaces built with a) set 4 and b) set 9.

SEM images for two upward-facing surfaces can be seen in FIGURE 3. FIGURE 3a) shows the upward-facing surface built with set 4. Similar to the vertical surface with the same set, this surface is dominated by partially melted powder particles but the re-solidified material from the melt track as well as gaps in the melt surface can be seen.

FIGURE 3b) shows the upward-facing surface built with set 9. This surface is dominated by the re-solidified material from the melt track with

very few partially melted powder particles. There is no deformation of material that was seen in the vertical and downward-facing surfaces. Additionally, there is little evidence of the layers or of any stair-stepping phenomenon commonly associated with AM.

It is interesting to note that vertical, upward-facing, and downward-facing surfaces built with set 4 are all very similar qualitatively. The selection of this parameter set for the contours would make sense for a manufacturer if having a consistent exterior surface, regardless of position or orientation, is the desirable outcome.

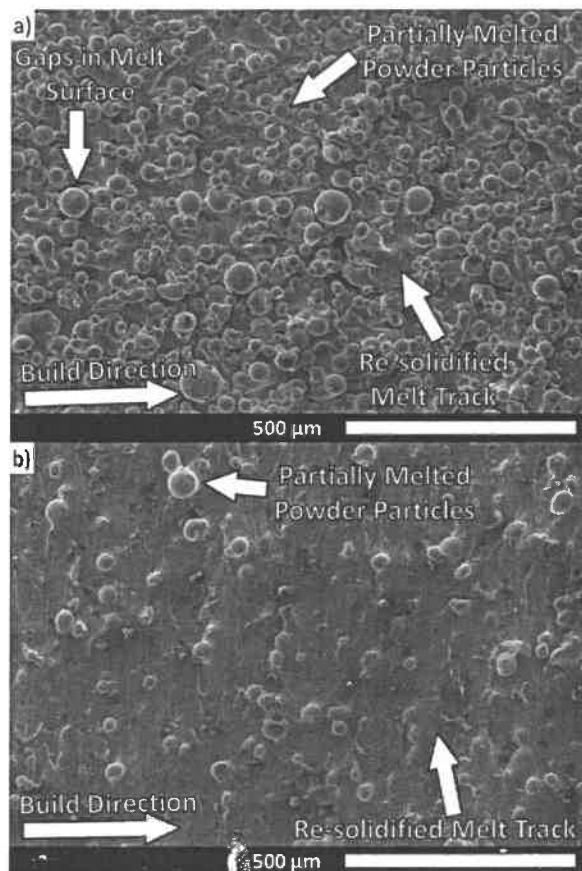


FIGURE 3. Upward-facing surfaces for $\alpha=60^\circ$ built with a) set 4 and b) set 9.

Quantitative Analysis

Vertical Surface Analysis

Analysis of Ra for the vertical surfaces can be seen in FIGURE 4. As mentioned previously, these parallelepipeds were built such that the downward-facing surface forms a straight line to the center of the plate. Therefore, the vertical surfaces are either facing towards the center of

the plate (labeled Towards) or away from the center of the plate (labeled Away).

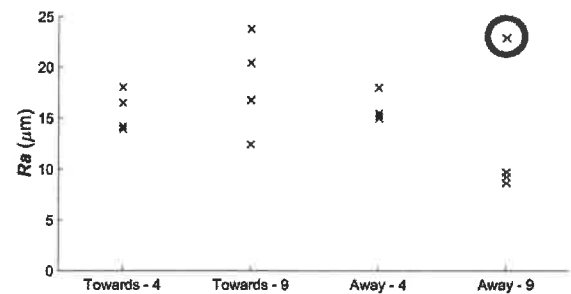


FIGURE 4. Ra vs orientation relative to the center of the build platform and contour parameter set for the vertical surfaces. Outlier described in text is highlighted by a red circle.

FIGURE 4 shows that it is difficult to develop a physical interpretation of the surface through Ra alone. An interesting observation, however, is that the high value outlier for the Vertical Away surface built with set 9 (highlighted by the red circle) could be due to the orientation relative to the recoater blade. Three of the vertical surfaces facing away from the center of the plate and built with parameter set 9 were oriented such that the recoater blade was going into the surface when spreading powder, while the outlier was oriented such that the recoater blade was coming out of the surface. Thus, the increase in surface roughness could be due to damaged material protruding from the surface and additional qualitative analysis is required to confirm.

Analysis of Rc and RSm for the vertical surfaces can be seen in FIGURE 5. Little variation can be seen in Rc and RSm for the parts built with set 4. For set 9, there is an increase in RSm when compared to set 4, which is expected from SEM images as the surface for set 9 is dominated less by partially melted powder particles and more by the re-solidified material from the melt track.

Another interesting finding is the difference in Rc for set 9 depending on whether the surface is facing towards or away from the center of the plate. This suggests that there is also a positional dependence in the Rc parameter, similar to what was seen by Kleszczynski *et al.* [14], but more qualitative analysis of the surfaces is required to determine the cause of this change.

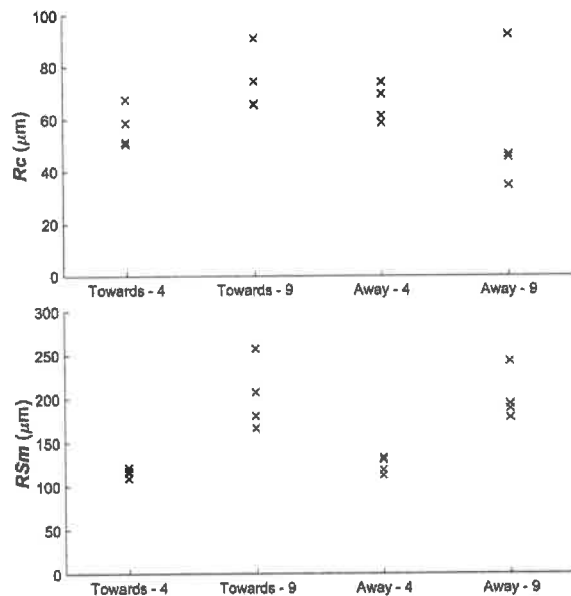


FIGURE 5. R_c and R_{Sm} for the vertical surfaces.

Upward-Facing Surface Analysis

Analysis of R_a for the upward-facing surfaces as well as the downward-facing surfaces from prior work is presented in FIGURE 6 [16]. As was seen in the prior work, it can be difficult to discern differences in R_a from process parameters for the downward-facing surfaces. The upward-facing surfaces, however, exhibit a noticeable difference in R_a . Additionally, R_a for the upward-facing surfaces built with set 9 decreases as α decreases. This is likely due to the extremely small number of partially melted powder particles seen in SEM images, causing R_a to be dependent almost entirely on the re-solidified melt track.

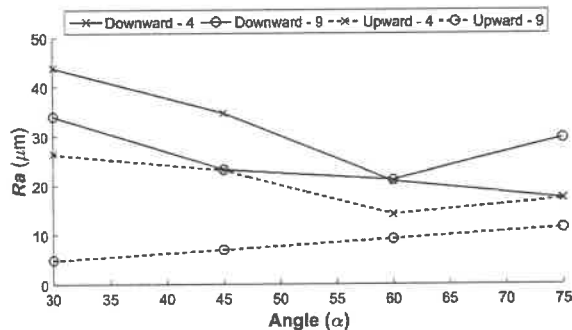


FIGURE 6. R_a vs angle for downward- [16] and upward-facing surfaces.

Analysis of R_c and R_{Sm} for the upward-facing surfaces as well as the downward-facing surfaces from prior work can be seen in FIGURE 7 [16]. As expected, R_c decreases and R_{Sm}

increases as we move from surfaces dominated by partially melted powder particles to ones dominated by the re-solidified melt track.

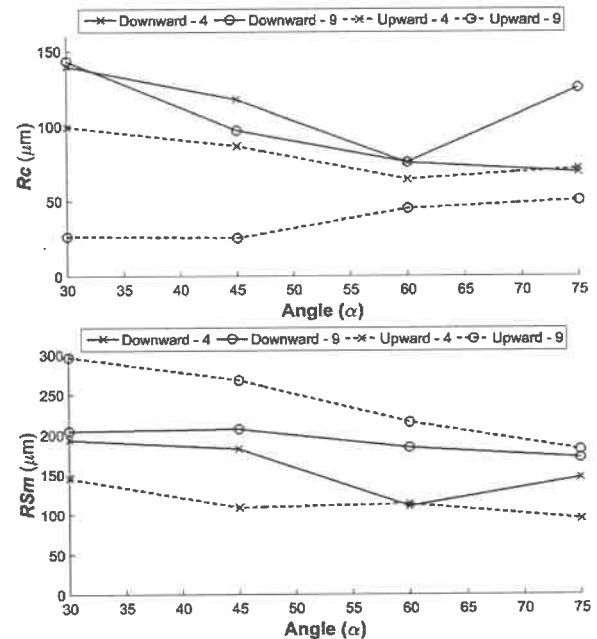


FIGURE 7. R_c and R_{Sm} vs angle for downward- [16] and upward-facing surfaces.

CONCLUSIONS

Analysis of upward-facing surfaces of 30°, 45°, 60°, and 75° relative to the build platform and vertical surfaces (90° relative to the build platform) was performed qualitatively by SEM and quantitatively by white light interferometry. Samples were built with two power and velocity combinations, which were found by prior work to create drastic changes in the surface features for downward-facing surfaces [16]. As with the downward-facing surfaces, R_a was shown to provide little insight into characteristics of the vertical and upward-facing surface. R_c and R_{Sm} for the vertical and upward-facing surfaces, however, showed similar correlations to the downward-facing surfaces where R_c increases and R_{Sm} decreases as surfaces change from being dominated by the re-solidified melt track to those dominated by the partially melted powder particles. While additional experiments and analysis are required to match specific surface features with the physical process of L-PBF, these correlations provide insight into the use of surface texture as a process signature.

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ON THE METROLOGY OF SURFACES PRODUCED BY LASER MELTING OF POWDERS

**Adam C. Lemoine, Matthew P. Mancini, Joseluis A. Velez, and
Christopher A. Brown**
Surface Metrology Laboratory
Mechanical Engineering Department
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

INTRODUCTION

The objective of this work is to advance surface metrology and the understanding of the relations between processing and surface topography of parts made by laser melting. These relations are valuable, because they support the design of additive manufacturing processes that can influence the resulting surface roughness. These relations must be established through the discoveries of correlations between surface topographies and process parameters, which must be done experimentally.

This paper examines the proposition that strong correlations of this kind, between topographies and processing, or performance, are facilitated by adherence to four principles of topographic characterizations:

1. characterization of the appropriate geometric features;
2. characterization in the appropriate scale ranges;
3. characterization applying appropriate statistical analyses to these geometric features at these scales;
4. characterization of measurements with sufficient fidelity to the surface over these scale ranges.

These principles are based on a model in which many microscopic, discrete interactions, which occur at some small, fundamental scales, can be summed to compose the performance observed macroscopically at larger scales.

An assessment of the state of the art for examining these principles and the discrete interaction model logically should evaluate the scale and geometric nature of the characterizations, as well as the strength of the correlation coefficients between the processing parameters, or macroscopic performance parameters and the characterizations of the surface topographies. It is important to identify,

insofar as possible, the parameters that influence the scales of the fundamental interactions between the surface topography and the manufacturing process that produce the surface topography.

Grimm et al. [1] correlated hybrid parameters, such as the developed surface area ratio, S_{dr} , and the average slope, S_{dq} , (ASME B46.1 2009 and ISO 25178), with the inclination angle of surfaces manufactured using laser beam melting. S_{dr} and S_{dq} are calculated using the finest scales in the measurement. They also correlated the root-mean square flatness (FLT_q), the waviness parameter, W_{sa} , and average roughness, S_a , with the inclination angle of sintered surfaces. These height parameters are sensitive to the largest scales in the filtered measurement, which would depend on the waviness and form cut offs or nesting indices (λ_s and λ_f respectively). The fractal dimension by the box counting method also correlated well with the inclination angle of the laser melted surfaces [1]. The box counting method relies on a distortion of the surface measurement in the vertical direction, which was not reported.

Multi-scale geometric analyses have been used by Zeng et al. [2], who attempted to correlate surface topographies with angles in fused deposition modeling. Strong correlations between an adjusted layer thickness and the smooth-rough crossover (ASME B46.1 2006) calculated using area-scale analysis (ASME B46.1 2006, ISO 25178-2) were found [2]. Brown and Burns also attempted to quantify the influence of outliers on the ability to discriminate surfaces manufactured by laser sintering [3]. Their results show that outliers in the measurements of additive manufactured surface measurements can influence the ability to discriminate. Many of these outliers are created around the edges of partially sintered particles.

Hyde et al. found strong, scale-specific correlations between the discharge energy used to manufacture surfaces by micro-EDM and relative area and complexity have been found using multi-scale geometric analysis [4]. This was also on re-solidified surfaces, although those surfaces were melted from a solid by electric discharges rather than powder by laser.

METHODS

Several 10x10x10 mm cubes with rounded edges on the top, with a nominal radius of 5 mm were manufactured on a Concept Laser M2 as shown in Fig. 1. Inconel alloy 718 powder was used with particle diameters ranging from 30 to 50 μm . The contour scan speeds were 400 and 1600 mm/s and the laser powers were 100 and 180 watts. This resulted in a four different linear energy densities as shown in Table 1 [5].

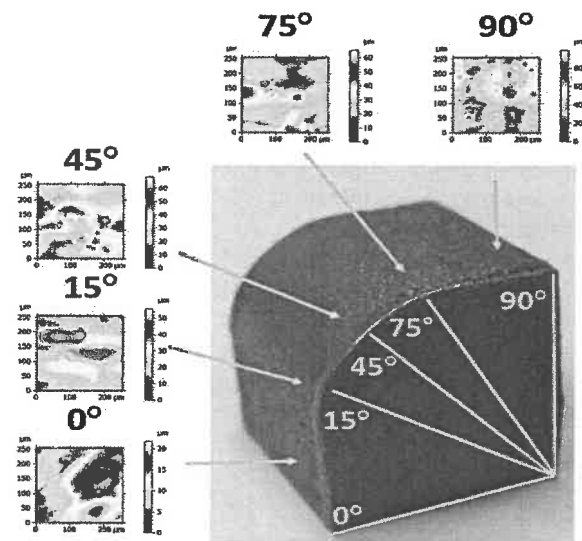


FIGURE 1. The geometry of the manufactured 10x10x10 μm cubes showing the orientations of the measurements with examples from a surface made with an LED of 0.0625 J/mm.

TABLE 1. Laser treatment parameters. The LED is the linear energy density, which is equal to the power divided by the speed.

Power (Watts)	Speed (mm/s)	LED (J/mm)
100	1600	0.0625
180	1600	0.1125
100	400	0.25
180	400	0.45

An Olympus LEXT 4100 scanning confocal microscope with a 50x objective (0.95 numerical aperture, NA), was used to measure the topographies over a region of 256x256 μm with a sampling interval of 250 nm. Measurements were made on the side 0° and top 90° and at 15°, 45° and 75° around the rounded upper edge.

Because outliers are a known issue when measuring laser melted powder topographies [3], two kinds of outlier filters were used. One was an outlier filter in MountainsMap (Digital Surf, 2015) where isolated outliers and outliers around edges were removed, and the resulting non-measured points were filled in by interpolation in MountainsMap. Additionally, a modal-based filter was used to remove outliers from the surface measurements [6]. Three different mode numbers were used (125, 250, and 500), with a confidence interval of 0.001.

Conventional height parameters were calculated for each surface measurement. Linear regression analyses were performed between each conventional parameter and the linear energy densities, and the regression coefficients, R^2 , were calculated. Area-scale analyses were performed on each unfiltered and filtered surface measurement, and the relative areas were calculated as a function of scale (ISO 25178-2, ASME B46.1). The relative areas were regressed against the linear energy densities (LEDs) at each scale available in the measurements. These scales extend from the sampling interval to the size of the measured region. Regression analyses were performed on filtered and unfiltered measurements at each inclination angle.

RESULTS AND DISCUSSION

A rendering of a measurement taken from a surface made with an LED of 0.25 J/mm is shown in Fig. 2. The curvature has been left in. Striations can be detected from lower right to upper left on the image. A fine-scale speckling on the image can also be detected, which can be a sign of partly fused powder causing the “bumps” that Lou et al. studied using watershed segmentation [7].

The strongest correlations found from the linear regressions that were carried out for topographic characterization parameters versus LED, for conventional and multi-scale areal parameters,

i.e., relative area and area-scale complexities, are summarized in Table 2 [5]. Fig. 3 shows some of the plots on which these are based.

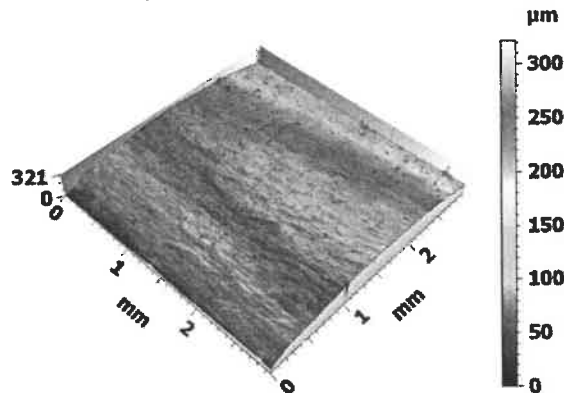


FIGURE 2. Rendering of measurement of a surface with an LED of 0.25 at an angle of 45°, stitched (5x5 measurements, 2.94x2.94 mm) using 20x objective (0.6 NA) and a lateral sampling interval of 624 nm.

Depending on the method of filtering, several surface conventional height characterization parameters are capable of correlating strongly with the linear energy density on the top of the cube (90°). The strongest correlation was with relative area at a scale of about 3,000μm² [5].

TABLE 2. Results of regression analyses. The "deg." indicates the inclination angle as shown Fig. 1. All correlations are negative.

Parameters	deg.	R ²	Filtering
Rel. Area	90	0.999	Unfiltered
Sku	90	0.996	Unfiltered
Sv	90	0.978	Mountains
Sku	90	0.973	Mountains
Sv	90	0.958	Unfiltered
Complexity	0	0.957	Unfiltered
Sv	90	0.950	Modal: 125
Sa	75	0.921	Modal: 500
St	90	0.913	Unfiltered
Sa	75	0.911	Modal: 125
Sa	75	0.910	Modal: 250
Sv	90	0.898	Modal: 500
St	90	0.890	Mountains
St	90	0.888	Modal: 125
Rel. Area	0	0.880	Mountains
Sdq	90	0.876	Modal: 125
Sp	90	0.871	Unfiltered
Sv	75	0.871	Unfiltered
Sv	90	0.857	Modal: 250

The equations for the regressions shown in Fig. 3 are given below:

$$\begin{aligned}
 St &= -178.09 \cdot LED + 121.94 \\
 Sp &= -103.87 \cdot LED + 73.005 \\
 Sv &= -74.214 \cdot LED + 48.935 \\
 Sku &= -3.0564 \cdot LED + 3.449
 \end{aligned}$$

Note that St, peak to valley height, is the sum of the peak height, Sp and the valley depth, Sv. This is true for the individual parameters as well as the equations above.

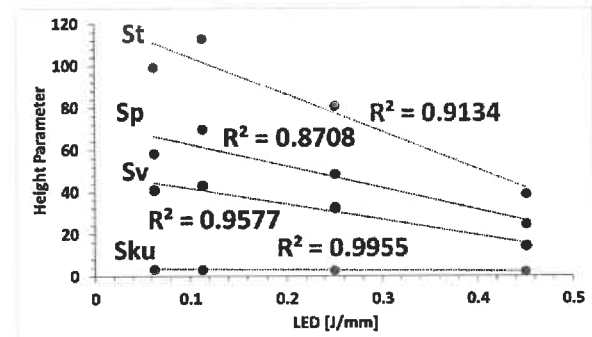


FIGURE 3. The correlations between the height parameters and LED at 90° unfiltered. The units on St, Sp and Sv are μm. Sku is unitless.

Plots of the relative area versus the scale, i.e., the size of the virtual tiles used to calculate the relative areas, which are the ratios of the areas calculated from tiling to nominal or projected areas were generated. At the largest scales, half the size of the measured region, the relative areas is one. The finest scale is half the square of the sampling interval. The increase in roughness as the angles exceed 45° is remarkable and suggests challenges in process design to achieve acceptable surfaces at these angles.

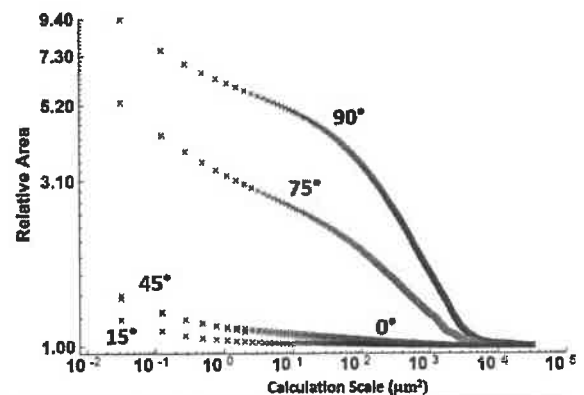


FIGURE 4. Area-scale plots for unfiltered surfaces with an LED of 0.25 J/mm and several inclination angles.

The correlation coefficients, R^2 , between the relative areas and the LEDs for the side and top (0° and 90°) are shown in Fig. 5 as a function of the scales of the relative areas used in the calculations. At an inclination angle of 90° , the correlation coefficients exceed 0.95 within a scale range of 1,906.53 and 3,528 μm^2 [5]. The R^2 curve increases steadily to this relative maximum from the fine scales. This indicates that the features driving this correlation are large. This is consistent with the strong correlations seen for the conventional height parameters, which tend to be sensitive to the larger scales in the measurement.

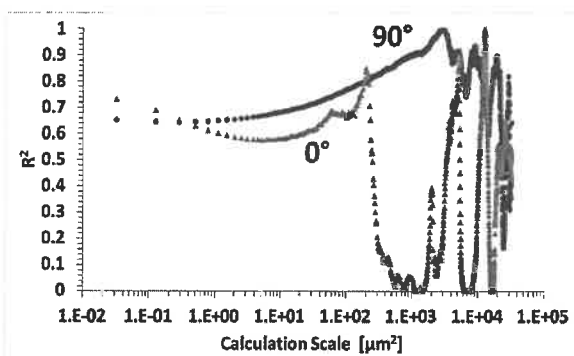


FIGURE 5. Correlation coefficients, R^2 , for correlations between relative area and LED versus scale on unfiltered surfaces at 0° and 90°

Only relative area and complexity were capable of finding strong correlations with the surface on the side of the cube (0°) [7]. This could be because the correlation in this case is at a lower scale where the traditional height parameters are not so sensitive. This supports the scale principle, the second of the principles presented previously.

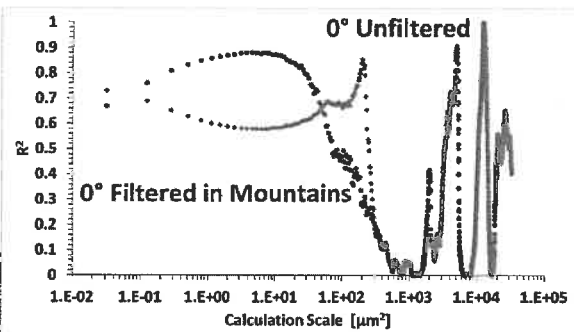


FIGURE 6. Correlation coefficients R^2 between relative areas and LEDs at 0° , unfiltered and filtered in MountainsMap.

Only S_a and S_v were found to correlate well when used with several filtering methods at an inclination angle of 75° . The filtering could be said to provide a kind of scale specificity, and in that sense those results could be said to support the scale principle, although this appears to be a bit of a stretch. Also height parameters do not define geometries particularly well, so in this sense the geometric principle is not well supported by those results.

The fidelity principle appears to be supported by the filtering efforts to remove outliers and the improved correlations in those instances.

Fig 6. shows that the influence of filtering using MountainsMap is to reduce the scale of the strongest correlation. This would be consistent with removing larger scale features in the measurement. Filtering does not appear to appreciably improve the strength of the correlation however [5].

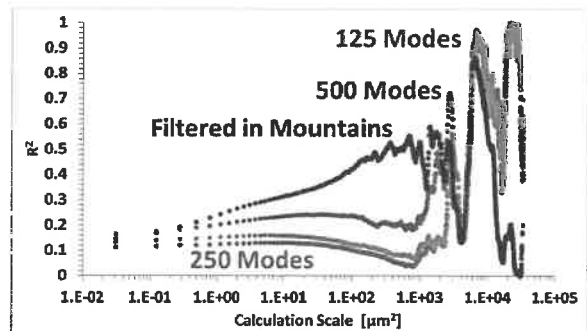


FIGURE 7. Correlation coefficients R^2 between relative area and LED at 75° for three different mode filters and in MountainsMap.

Fig. 7 shows the influence of the filtering parameters on the strength of the correlations. The modal filters result in the same pattern of regression strengths until a scale of about 4,000 mm^2 where the filtering with the greatest number of modes picks up a local maximum in correlation strength missed by the 250 and 125 modes filters [5]. This is about the same scale where regressions from measurements treated with the MountainsMap filter follow the modal filters momentarily.

Fig. 8 shows the two plots with the strongest correlations for the top (90°) and second strongest for the side (0°). Both of these are with relative areas and the latter is filtered while the former is not. Relative area is an appealing geometry for finding correlations, because it is

sensitive to the slopes on the surface left by the solidification. As more energy is transferred to the surface with greater LEDs, the melting of the powders should be more complete and the opportunity for the melt pool to flow under the influence of surface tension and gravity. Logically this would result in a smoother surface, with lower inclinations, hence smaller relative areas with greater LEDs. This is consistent with the geometric and scale principles (first and second).

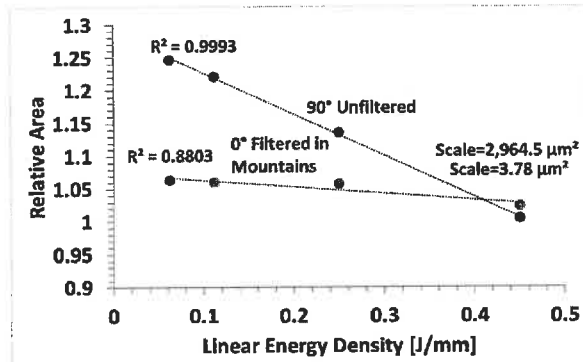


FIGURE 8. Relative areas determined at the two scales and filtering, as shown in Figures 5 and 6 with the strongest correlations from the top (90°) and side (0°) at specific scales between the relative areas and the LEDs.

Fig. 9 shows the complexity, which is the change in relative area with respect to scale, as a function of scale. The complexity is similar to the fractal dimension (ASME B46.1 2002).

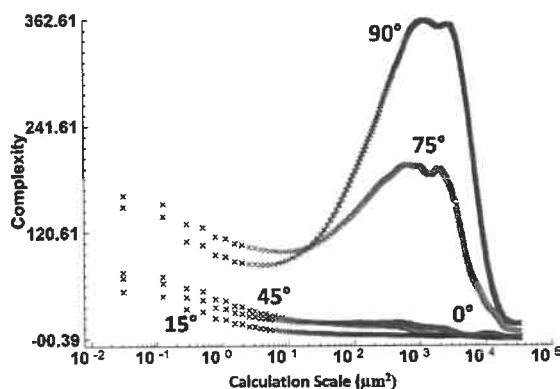


FIGURE 9. Complexity as a function of scale for the unfiltered surfaces with an LED of 0.25J/mm and several inclination angles.

The more horizontal surfaces have markedly greater complexities at the larger scales (Fig. 9).

This seems like it might be consistent with the powder particles, although this does not explain why the surfaces closer to vertical do not show the same tendency. At the finest scales all the surfaces display a tendency for increasing complexity with decreasing scale.

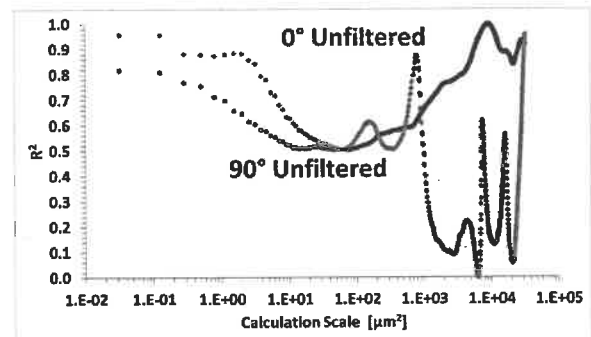


FIGURE 10. Correlation coefficients, R^2 between complexity and LED at 0° and 90°.

Fig. 10 shows especially strong correlations with complexity and LED at the largest and finest scales. This result could be helpful for understanding the process and how the surfaces formed, supporting process and tool design.

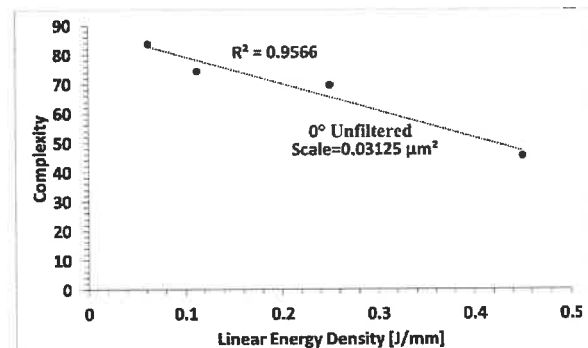


FIGURE 11. The strongest correlation coefficient between complexity and linear energy density obtained at a fine scale, 31,250 nm², for a measurement on the side (0°).

Fig. 11 shows a plot of area-scale complexities versus LEDs at the scale of strongest correlation, 31,250 nm². This is the strongest correlation for the roughness on the side of these parts. The next strongest correlation is with the relative area. These results support the scale principle, proposed previously. The knowledge of the scales of strongest correlation and the geometry of the characterization can also promote understanding of the process,

especially when considering the melting of a particle and layering as discrete events. This would apply to the correlations at the large scales. At the fine scales it is tempting to consider the cooling and solidification as potentially texture forming processes.

CONCLUSIONS

1. Several topographic characterization parameters are found to correlate well with a process parameter, linear energy density.
2. The strength of the correlations depends on the filtering, scales, and the characterization parameters.
3. The multi-scale geometric parameters appear to be the most useful for providing insights for understanding how the process might influence the resulting topographies.
4. The results of this work appear to support the proposed principles for discovering correlations in surface metrology, which are: to characterize the appropriate geometry, at the appropriate scales, while applying appropriate statistics, and using a measurement with sufficient fidelity at those scales.

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PRACTICAL METHODS OF CORRECTING X-RAY CT SCANS

David J. Bate,
Engineering Department
Nikon Metrology
Tring, Hertfordshire, UK

INTRODUCTION

Within X-ray CT and CT metrology on all types of materials there are a number of known errors e.g. Beam hardening, scattering, cone beam artefacts etc. Some of these errors are inherent to the technique and so are difficult to remove, however, some of these errors can be reduced or minimised with practical solutions.

This paper will look at a sample of errors that can be reduced or removed by practical changes to the CT scanning process or the post processing. The error sources to be considered will be (1) Beam hardening (2) Geometry errors and (3) Scattering

BASICS OF X-RAY CT

X-ray CT consists of the process of irradiating an object with X-rays and moving the object relative to the X-rays in a motion that generates a number of projections of the image at different angles.

The most common mode today is based on a circular geometry leading to projections at a variety of angles. These projections are then combined computationally to create a volumetric data set where each Voxel (three dimensional pixel) is assigned a number depending (Approximately) on the density of the material.

This is normally achieved using a filtered backprojection method [1].

The key equation in all X-ray CT is

$$I = I_0 e^{-\mu t}$$

Where I represents the intensity of X-rays, μ is the attenuation coefficient and t is the thickness of material.

The reconstruction process calculate the attenuation $\ln(I_0/I)$ for each ray in each projection and uses the data to calculate the attenuation in each voxel.

ERROR 1: BEAM HARDENING

Background

The first error source to be considered will be the Beam hardening effect. This is a well known effect in microfocus X-ray systems as the method of X-ray generation leads to polychromatic beams and so the absorption becomes non-linear.

This changes the simple attenuation relation introduced above to the more complex

$$I = \int I_0(E) e^{-\mu(E)t} dE$$

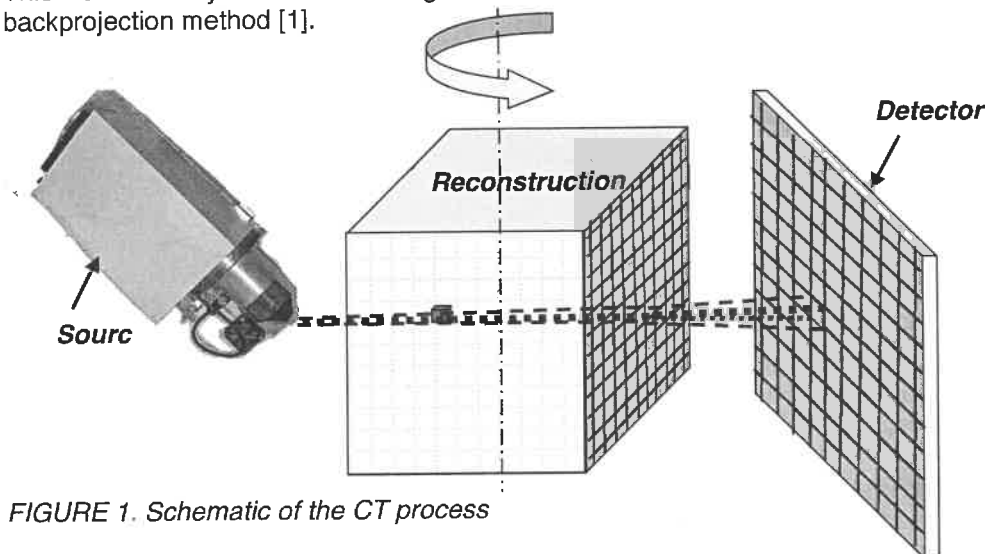


FIGURE 1. Schematic of the CT process

Solving this equation is very difficult as the X-ray spectrum of the source is not simple to measure or calculate.

If these errors are not corrected regions of the interior of the object will appear to be less dense than the surface layer which leads to problems finding a surface, particularly for interior edges (voids, inclusion etc).

Correction 1: Physical Filtration

The first method by which this error can be reduced is by placing thin foils in the beam.

The effect of these foils is to attenuate the beam, as the beam is not a simple flat spectrum the filter will preferentially remove low kV X-rays that would be stopped by longer paths in the beam and will move the peak of the spectrum to higher energies and make the beam monochromatic. Figure 2 compares an unfiltered beam with a filtered beam (not to the same scale) to illustrate the method.

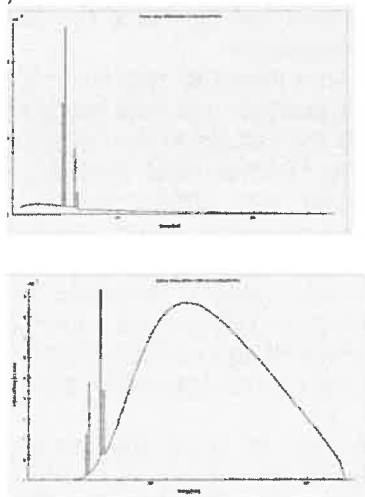


FIGURE 2: Comparison of X-ray spectrum through filtering. Upper image unfiltered mean energy 77 kV, lower image filtered 3mm Cu mean energy 130 kV

Correction 2: Post collection correction

It can be seen in the above, that even with optimum filtration there will still be an error due to beam hardening, it can be made very small and in many practical cases physical filtration is sufficient.

However, for those cases when physical filtration is insufficient or impractical there is a second approach. In this approach the basic equation is considered in a slightly different form

$$\ln(I_0/I) = \mu t$$

In this form it can be seen that a plot of the attenuation taken as the natural log of the intensity ratio should be a straight line with slope given by the attenuation coefficient.

In this form the beam hardening problem is shown as a deviation from a straight line, as shown schematically in figure 3

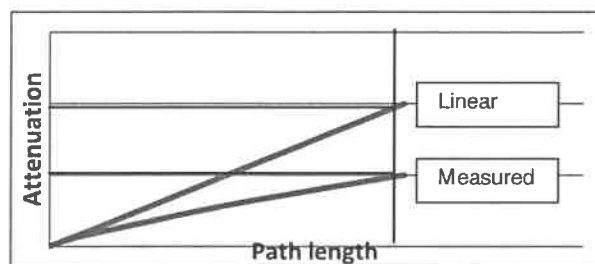


FIGURE 3: Drop of measured attenuation from ideal (linear) attenuation

In this case it is possible to correct the collected data by calculating a correction from measured to linear attenuation. This can be done by measuring the actual attenuation versus thickness of material and plotting the measured curve from figure 3. Then by estimating the slope as the path length tends to zero to estimate the linear slope a series of estimates can be found for the actual attenuation at a given measured attenuation. These can then be fitted by a polynomial and used to correct the data.

$$\ln(I_0/I)_{Actual} = \sum \alpha_n \ln(I_0/I)_{Measured}^n$$

Depending on the material and the accuracy needed different n can be used. Typically, for most materials a value of n no greater than 4 is sufficient.

This method has a couple of drawbacks

- 1) It only works well on single material samples
- 2) It assumes that you can actually extract the path length t and the attenuation at that path length from the data, or from separate measurements

However, this is a very powerful method, particularly when used with single material samples that are repeatedly scanned so the correction can be improved by each scan.

The combination of the post-acquisition correction with the physical filtration will give a much better result for the volume and so lead to much better and more accurate measurements of the sample in practical scans without having to use a fully monochromatic beam.

Error 2: GEOMETRIC ERRORS

Background

In order to make quantitative measurements of CT scans it is critical to know the geometry of the system and know that it is fixed.

If the System is well set up, aligned and calibrated the remaining Geometric Unsharpness in each projection is given by:

$$\text{Geom. Unsharpness} = \sqrt{\left(\frac{p \cdot d}{D}\right)^2 + \left(\frac{s \cdot (D - d)}{D}\right)^2}$$

Where p = pixel size, s = X-ray source spot size (FWHM of equivalent Gaussian), d = the X-ray source to object rotation axis and D = X-ray source to detector active plane. In terms of the Magnification $M = D/d$

$$\text{Geom. Unsharpness} = \frac{1}{M} \sqrt{(p)^2 + (s(M - 1))^2}$$

By inspection it can be seen than at low magnifications (M close to 1) then the pixel size will dominate the unsharpness and that for high magnification (M very high) the spot size will dominate the unsharpness.

The effects described so far are those which are unavoidable. In addition there are a number of contributions to unsharpness that can be avoided.

- 1) Geometry knowledge, the above equation assumes that the 4 parameters s , p , D , d are accurately known. If this is not the case then the accuracy of the resulting data will be significantly impaired.
- 2) In the above it is assumed that everything is aligned, i.e. the rotation axis is perpendicular to the X-ray axis, the detector plane is perpendicular the the central X-ray axis
- 3) It is assumed that the geometry doesn't change with angle.
- 4) More generally systems will assume that the if the geometry is known at one position then the readback from the manipulator will allow calculation of the position accurately at every other position. This may not be the case due to backlash or other imprecisions in the mechanical drive train.

Correction 1: Initial setup

The first way to avoid such errors is to make certain that the system to be used for

measurement is well setup. This can mean taking the following steps:

- 1) Use a laser interferometer to calculate the errors in an axis versus the encoder read back and apply a correction
- 2) Use standard mechanical alignment tools to adjust all axes for perpendicularity
- 3) Use a test sample to adjust the X-ray axis position relative to the mechanical geometry.

By taking these steps before starting any piece of work then the system will start from a good state (NB these setups are performed in advance on most manufacturers metrology systems)

Correction 2: Comparative check

If a system is not a dedicated metrology system or there are known issues then the best way to get an enhanced accuracy is to use the system more as a comparator.

In this method a traceable test piece is scanned at the same position and with the same X-ray conditions as the sample to be measured.

By identifying Unidirectional measurements on the test piece (i.e. Sphere centre - centre distances) the geometric magnification (or voxel size) can be accurately calculated.

Provided the test piece is the same material as the sample then bi-directional measurements can be performed to set the threshold for the surface to give the most accurate results.

The combination of these two techniques can give accuracies on a given work piece that are better than the quoted MPE of a system.

ERROR 3: SCATTERING

Background

When X-rays interact with matter there are several process taking place

- 1) Absorption – this is the desired mechanism for generating X-ray contrast in radiographs and projections for X-ray CT
- 2) Elastic scattering – this mechanism scatters X-rays out of their straight through ray path and so introduces an error in the strict attenuation
- 3) Inelastic scattering (Compton)– This mechanism scatters X-rays out of their original ray path and so reduces the

signal along the ray but increases the signal at a different pixel.

- 4) Pair production – the X-ray causes a particle pair to be produced. This mechanism can currently be ignored in microfocus X-ray as it doesn't exceed the minimum energy, but this is a problem for LINACs and Synchrotrons of sufficient energy.

The effect of these mechanisms on the X-ray beam varies with X-ray energy as shown in Figure 4, as can be seen at low energies it is the first two categories that dominate and so scatter is a minor error but not a critical problem. However, as the energy rises the scattering becomes more of an issue as more X-rays are scattered out of the beam and into the wrong pixel.

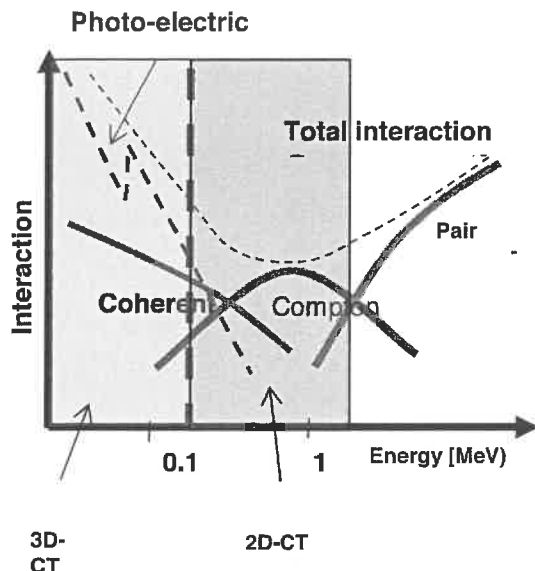


FIGURE 4: Comparison of scattering contributions with energy.

In Figure 4 two region are identified. In the lower energy region scattering is a minor error and 3D CT images are not significantly affected. As the energy increases the ratio of the scattered to unscattered primary radiation increases and steps must be taken to remove the scattered radiation, if steps aren't taken the contrast in the final image will be poor and so the definition of the projections will lead to errors in the final volume and hence measurement

Correction 1: Collimation

The first method to reduce scatter is to collimate the beam. The aim of collimation is to remove unnecessary X-rays from the system so that they cannot scatter and then to remove scattered X-rays from the image so that the contrast is retained

The first part of the collimation is to place a collimator on the X-ray source so that only X-rays that will reach the detector by direct travel enter the system. This will remove X-rays that will scatter off the manipulator, walls etc of the system and cannot contribute to the signal.

The second point for collimation is after the sample to make sure that X-rays scattered at large angles do not reach the detector, the ultimate form of this collimation is the linear detector where a single line of detection elements is surrounded by a collimator top and bottom so that very little scatter can reach the detector. Such detectors are often used as a practical solution at higher energies and for highly scattering objects (such as turbine blades) the increase in scan time is compensated by the accuracy of the data collected.

Correction 2: Post processing

The second method is to actually correct for the scatter in the image, to do this an estimate of the scatter contribution is needed and this can then be subtracted from the original image to obtain a scatter free projection.

There are several practical methods for implementing this [2] in the following the Beam Stop Method will be used as an example

In this method the following steps are taken:

- 1) Set up the system to scan the sample as a 3D CT as normal. Using collimation and best practice for other errors
- 2) Prepare a beam stop array (Grid of beam stops in a plastic matrix (see Figure 5))
- 3) Collect shading references with a dummy block of plastic with no beam stops
- 4) Take a radiograph of the block with beam stops to measure the attenuation of the beam stops
- 5) Take a CT scan of the object plus dummy block
- 6) Take a CT scan of the object plus beam stop array.
- 7) From (4) and (7) estimate the scatter at the centre behind each beam stop

- 8) Assuming that scatter is slowly varying use an interpolation method to estimate scatter at each point in each projection.
- 9) Subtract the scatter found in (8) from each projection in (5)
- 10) Reconstruct the projections in (9) to form a scatter free object

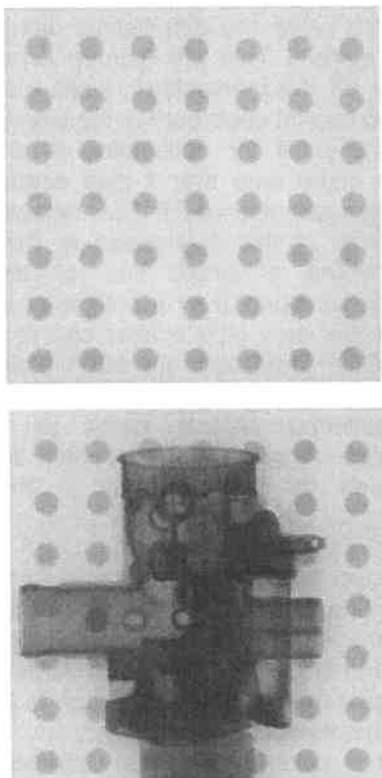


FIGURE 5: Example radiographs of the beam stop array and beam stop array plus sample from a scatter correction scan

Using such a correction method will give a much cleaner and sharper set of projection images and lead to a much better CT data set that is easier to measure.

CONCLUSION

In this paper a number of error sources in CT metrology have been considered (but not an exhaustive list) and practical methods have been suggested to minimize these errors to improve the measurements.

This paper has not looked at errors caused by the reconstruction and analysis of the volume in the software which is another potential source of errors.

It is hoped that a skilled operator applying these corrections methods could reliably produce a good data set.

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A SYSTEMS APPROACH TO QUANTIFYING UNCERTAINTY IN X-RAY SYSTEMS FOR METROLOGY

Jefferson A. Cuadra¹, Robert M. Panas¹
¹Lawrence Livermore National Laboratory

ABSTRACT

The use of X-ray computed tomography (CT) as a metrology tool for manufactured parts is still limited by the uncertainty of the measurements from the data acquisition and post-processing component. Most uncertainty studies have focused on measuring the difference between the imaged and actual part without considering the uncertainty effects from the X-ray system [1]–[7], i.e. hardware components, while others have only characterize specific components from the system [8]–[12]. This work attempts to characterize and quantify the uncertainty by implementing an uncertainty model based on a systems approach for each acquisition component (i.e. x-ray source, detector, and others). The ongoing modeling effort focuses on uncertainties in the attenuation value measured at a single pixel, which is a 0D point at the detector. This method is designed to be capable of extension to cover higher dimensional uncertainties with a target of mapping the full range of variation observed in X-ray radiographs. The current model includes the noise and sensitivities from mechanical vibrations, temperature variations, the electrical signal, and count rate at the source as well as at the detector. All of these uncertainties could potentially affect the performance of an X-ray system at a specific wavelength (energy level) for a single pixel measurement. The model also includes acquisition and calibration factors such as detector pixel cross talk, pixel binning and detector background noise. The overall use of this model could potentially provide feedback to the user about the different data acquisition components of the X-ray system resulting in optimization guidelines for better measurements.

BACKGROUND

X-ray CT is an optimal tool for various applications including three major fields: medical imaging, nondestructive characterization of materials, and dimensional and quality control assessments of manufactured parts [4], [13], [14]. Its increasing demand in manufacturing applications is due to the capability to nondestructively provide the measurement of inaccessible internal features of manufactured as well multi-material components and assembled parts permitting both dimensional and material quality assessment in a single task [15], [16]. Although its applicability in the medical and characterization fields meets the basic requirements, this is not the case for dimensional CT metrology since the accuracy and spatial resolution requirements and standards tend to be higher [2], [4], [13]. Furthermore, the X-ray CT measurements are influenced by many different parameters resulting in additional error sources to those in traditional techniques such as coordinate measuring machines (CMMs). Such errors and uncertainties are intrinsic of the experimental setup and the tomographic reconstruction algorithms implemented for data post-processing. Some of these error sources in the environment, x-ray source, detector and other components include the temperature, humidity, mechanical vibrations, beam hardening effects, quantum efficiency, threshold determination, and others [2]–[5]. A new uncertainty model that attempts to characterize and quantify the uncertainty from the dominant factors in each data acquisition hardware and software component is presented with the goal of optimizing the X-ray CT systems for metrology applications.

The model developed herein takes into account the contributions to signal variation as measured at a single pixel, including uncertainties and sensitivities from different sources and for each data acquisition X-ray component applying a systems approach [17]. The 0D model considers only errors which have no larger scale form, and thus do not require higher dimensional modeling. Inasmuch, the object is assumed to be a block of uniform thickness from the perspective of the studied pixel 'point' on the detector. Figure 1 displays the overall parameters included in the model for each X-ray system component in the form of a signal variation flow graph. For instance, the source includes mechanical vibrations at the source and with respect to the detector, ambient and component temperature effects, electrical current noise and source

emission variation which could affect the final emission of X-rays before they are recorded by the detector. Similarly, other noises are acquired in the transmission and detector regime due to the object attenuation and scattering as well as the efficiency and count noise of the detector. The signal variation flow graph also captures effects due to detector pixel cross talk, dark field offset (i.e. background noise of the detector) and a binning parameter in addition to a calibration term that normalizes the final response of the model output signal (Ψ_{output}). Furthermore, the signal variation flow graph depicts the use of low and high pass filtering to create a bandwidth of the noise parameters in the frequency domain when characterizing the power spectral density functions which are related to the variance of the output signal.

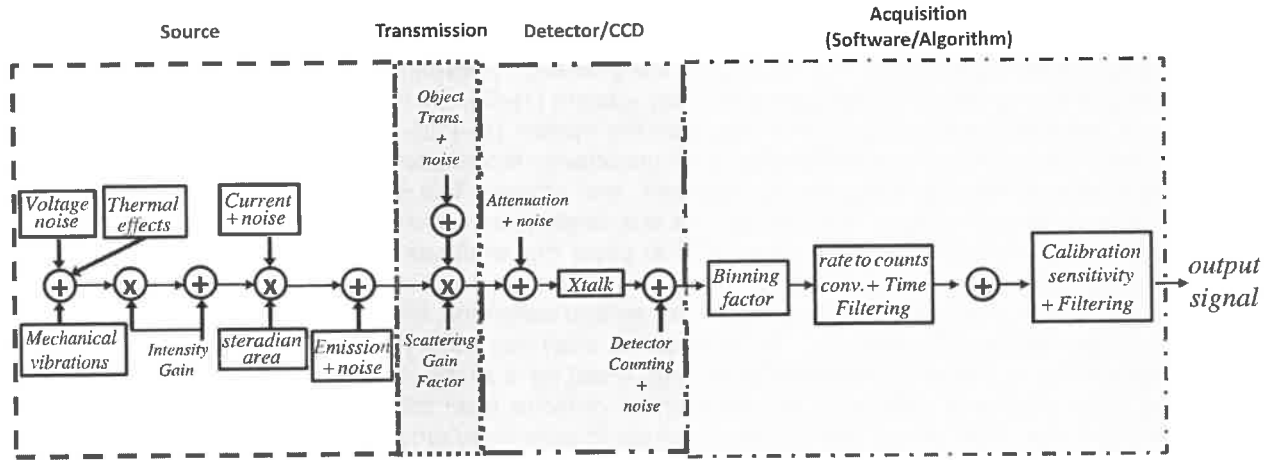


Figure 1: Signal variation flow graph representation with all parameters

The detailed variables used in each component of the model are depicted in Figure 2. This X-ray source component of the model can be simplified to:

$$r_{ps} = \sigma_{ns} + \frac{A_p}{z_{sd}} G_s \left(1 + \alpha_{Gs\theta_x} \sigma_{M\theta_x} + \alpha_{Gs\theta_y} \sigma_{M\theta_y} + \alpha_{GsV} \sigma_V \right) (\sigma_I + I_s) \quad (1)$$

where A_p is the pixel area as a function of the source coordinates, z_{sd} is the distance from source to detector, G_s is the X-ray intensity (flux) gain factor term, I_s is the current (for the case of electrically driven sources), $\sigma_{ns}, \sigma_I, \sigma_{M\theta_x}, \sigma_{M\theta_y}$ and σ_V are the noises from the emission variation, current, combined temperature and mechanical effects for θ_x and θ_y and voltage, respectively. Equation (1) also includes $\alpha_{Gs\theta_x}, \alpha_{Gs\theta_y}$ and α_{GsV} which are the sensitivity coefficients for the angular variation in θ_x and θ_y in addition to the source voltage. This submodel for the X-ray source also includes low pass filters for the temperature sensitivity coefficients. The final output for this part of the model is r_{ps} which is the count rate produced by the X-ray source. In the case of the model for the object/transmission effects, the number of uncertainties includes a theoretically calculated attenuation term (σ_{η_o}), a specific attenuation parameter value (η_o) of the object and a gain factor associated to scattering (G_{so}). The output signal, r_{po} , in count rate units for the transmission section can be represented by:

$$r_{po} = (\sigma_{\eta_o} + \eta_o r_{psl pf}) G_{so} \quad (2)$$

Additional submodels similar to the one from the transmission component can be formulated for optical filters in X-ray systems with an output signal as r_{pf} , since the uncertainty is originated by the reduction of

the count rate due to attenuation. The submodel for the detector describes the uncertainty measured by the noise due to the intrinsic efficiency (σ_{η_I}) and counts (σ_{ndc}) of the system. In the model, the zero mean variations (unbiased) relative to a parameter are represented as σ while biases relative to the parameter value upon system calibration are denoted as Δ . The systemic error due to the offset from the counts (Δ_{ndc}), a cross talk factor (G_{ct}) and the count rate signal from either the object transmission or optical filter ($r_{pol\ pf}$) are included in the X-ray detector submodel. The final signal yields (r_{pd}) in counts per second:

$$r_{pd} = \sigma_{ndc} + \Delta_{ndc} + G_{ct} (\sigma_{\eta_I} + \eta_I \cdot r_{pol\ pf}) \quad (3)$$

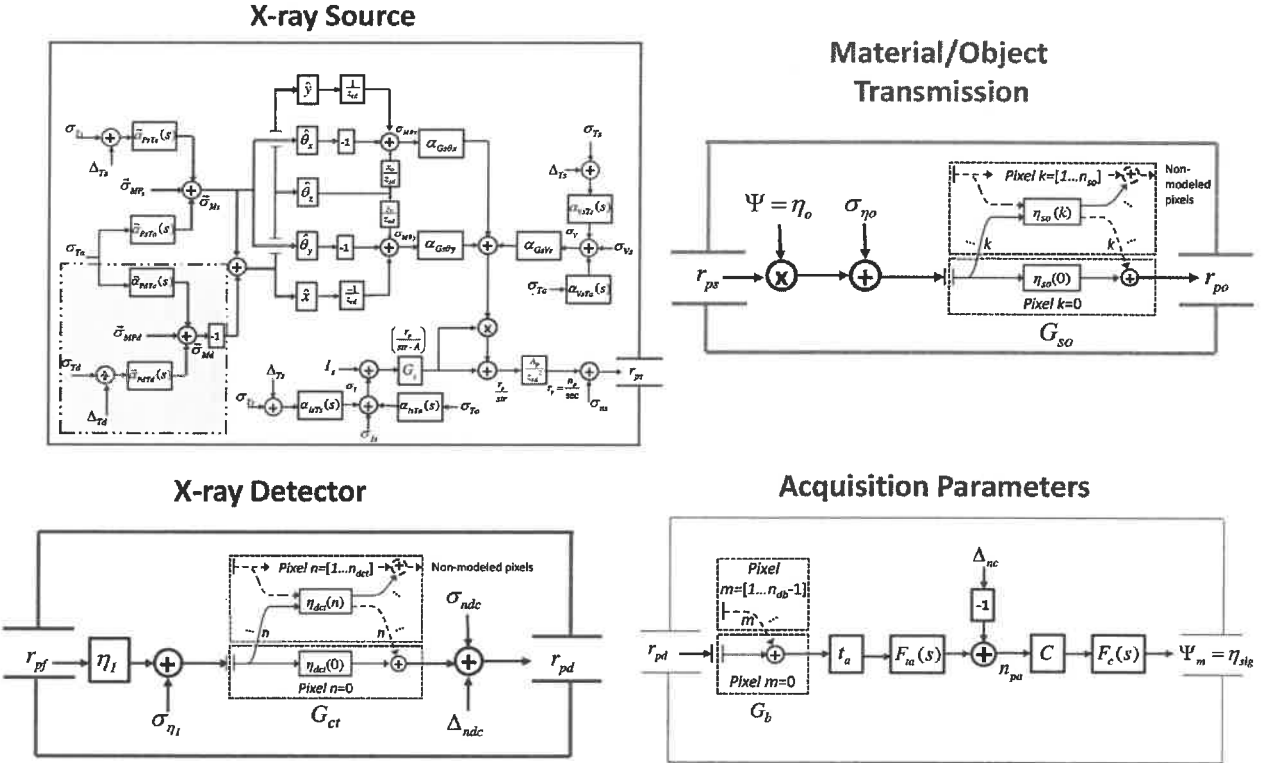


Figure 2: Signal variation flow graphs for all X-ray data acquisition components and corresponding parameters

Ultimately, the final output signal of the X-ray system is obtained by passing the signal from r_{pd} through a binning factor (G_b), converting it to counts by multiplying by the acquisition time (also referred as exposure time, t_a) as well as factoring a low pass filter (F_{ta}), applying a calibration offset (Δ_{nc}) and calibration factor (C) as well as implementing a high pass filter (F_c) adjusted by the time interval between system calibrations. The final equation (n_{sig}) gives an attenuation signal:

$$n_{sig} = F_c(s)C[-\Delta_{nc} + F_{ta}(s)t_a G_b r_{pd}] \quad (4)$$

RESULTS AND DISCUSSION

The preliminary results of the model were implemented using theoretical noise inputs from [17] and experimental data parameters from a customized micro CT system from LLNL [18]. The theoretical noises were power spectrum density functions for the mechanical vibrations, temperature effects and voltage noise. On the other hand, the current, exposure time, pixel area, source to detector distance as well as the measured bright and dark background field were obtained from a particular experimental setup. Figure 3a displays the background field of the X-ray source captured by the detector normalized by the current, steradian area, optical and object transmission, binning and cross talk factor as well as exposure time, referred to G_s in the model. Furthermore, Figure 3b shows the total uncertainty from the system calculated by adding all of the uncertainties from all submodels which denotes the confidence bounds to the unitless attenuation signal.

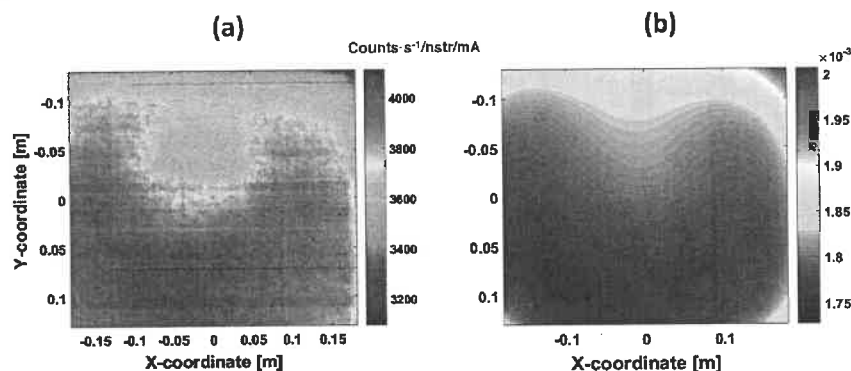


Figure 3: (a) Detector background field scaled to G_s in units of count rate per nanosteradian and milliamps, and (b) total noise of the system calculated from the model

It can be observed that both fields have similar trends with inverse values of each other which demonstrates that low intensity regions have the highest uncertainty values. In this particular quantification of the uncertainty, the output uncertainty are confidence bounds to a unitless attenuation value of 40% with a maximum value of 2×10^{-3} as shown by Figure 3b. In addition to quantifying the overall uncertainty, each uncertainty source can be calculated separately. Figure 4 shows the uncertainty calculated for the mechanical vibrations, temperature and electrical components.

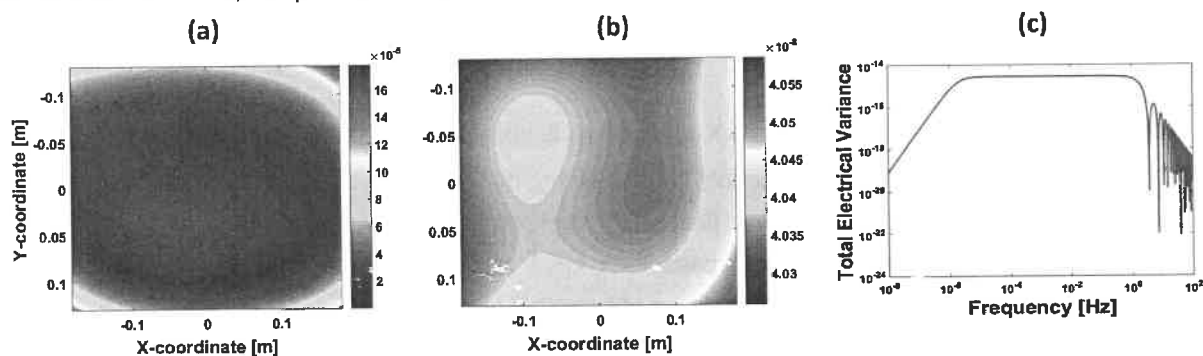


Figure 4: (a) Mechanical vibration, (b) temperature uncertainty field at each pixel with respect to the source plane coordinates and (c) electrical component variance in the frequency domain

The uncertainty field from the mechanical vibrations are dominated by the angular variation in intensity, $\alpha_{G\theta x}$, while the temperature uncertainty field depicts lower values with no dependence of any other field or input parameter. Other uncertainty sources in the X-ray source component are those from the voltage and current which are depicted as constant variance independent of the X-ray source coordinates, as shown in Figure 4(c), and yields a total uncertainty of 7.26×10^{-8} . Another three type of uncertainty sources that can be quantified separately consist of the source emission, object transmission and X-ray system

detector, depicted in Figure 5. These uncertainty sources are higher than those presented in Figure 4 being the emission noise the most dominant of all sources. In contrast to the other sources, these noises displayed a similar profile to that of the X-ray intensity gain factor field, G_s , which suggests that there is a one to one relationship between the flux of the X-ray system and uncertainty fields.

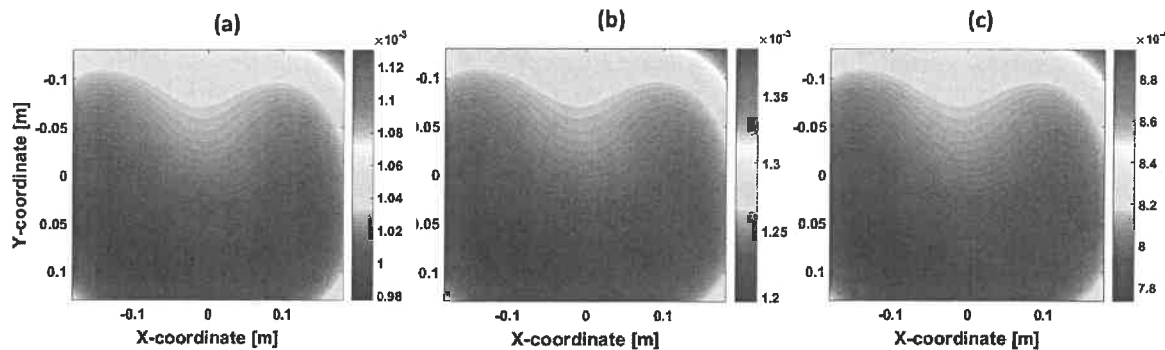


Figure 5: Uncertainty field from the (a) source emission, (b) object transmission and (c) detector counts

CONCLUSION

In these preliminary results, the uncertainty model was implemented to characterize and quantify the uncertainties spatially, i.e. at each pixel or X-ray source coordinate, for a specific X-ray system at a given energy level and acquisition parameters. This provides informative results which can potentially provide optimization guidelines to improve the performance of the X-ray measurements. Furthermore, the uncertainty model will be extended from OD (single pixel) to higher dimensional uncertainties with a target of mapping the full range of variation observed in X-ray metrology.

ACKNOWLEDGEMENTS

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Inspection of embedded internal features in additively manufactured metal parts using metrological x-ray computed tomography

Felix H. Kim¹, Herminso Villarraga-Gómez², and Shawn P. Moylan¹

¹Production Systems Group

¹National Institute of Standards and Technology

Gaithersburg, MD, USA

²X-Ray/CT Group

Nikon Metrology, Inc.

Brighton, MI, USA

INTRODUCTION

Advances in metal additive manufacturing (AM) have made it possible to build parts with complex geometry. Metal AM has a high potential to impact various industries including aerospace and automotive. Complex interior features can be designed to reduce weight and improve mechanical or thermal efficiency of the components. These features, however, are generally inaccessible from the outside to vision-based inspection techniques for quality control. Undesirable interior defects such as porosity and cracks can be formed due to sub-optimal processing parameters, poor feed stock material quality, or environmental effects [1-3]. The mission-critical structural components require thorough inspections for defects and dimensional accuracies.

X-ray Computed Tomography (XCT) – based inspection is becoming a viable option for several manufacturing industries. XCT shows a clear three-dimensional (3D) internal structure of the part in inspection. XCT has been popularly used to understand materials structure and behavior [e.g., 4, 5]. As the technique is applied to industrial inspection settings, guidelines must be established prior to widespread adoption of the technique.

To establish XCT as a reliable non-destructive evaluation tool for inspections of fracture-critical components, it is important to determine the base-line detectability of AM defect types and sizes using XCT. Probability of Detection (PoD) is a measure used to determine the capability of

a non-destructive evaluation (NDE) technique. There are yet undetermined aspects of PoD and minimum detectable flaw size for typical flaws found in AM-produced parts using XCT. Only a handful of papers related to this topic have been published to date [6]. One of the critical steps in evaluating non-destructive inspection techniques including XCT will be the ability to test parts with intentionally placed simulated flaws inside AM-produced parts. Reliable artifacts with internal features that are representative of the defects occurring in AM need to be developed. Building an internal structure, however, is difficult with any conventional technique. AM, on the other hand, provides an opportunity to embed complex internal structures.

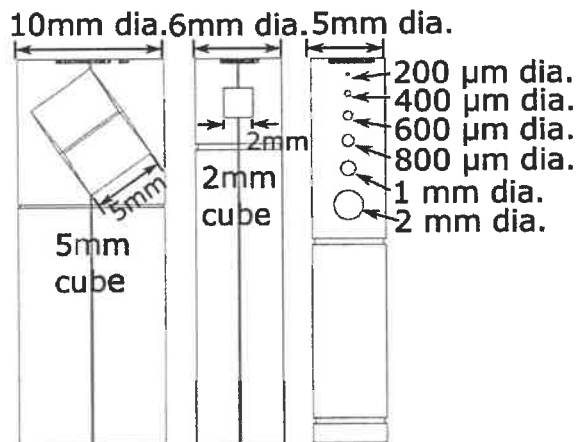
In this paper, an approach to build internal features using AM and to inspect the results using XCT are presented. Three test parts incorporating different internal features were built by a laser-based powder bed fusion (PBF) process. The qualities of these builds were determined from XCT scans. Metrological XCT scans measured the size of the internal features more accurately. The interior features were directly compared with the relevant computer-aided design (CAD) models. Based on the results, an improved artifact design is proposed.

LASER-BASED POWDER BED FUSION ADDITIVE MANUFACTURING OF SAMPLES WITH INTERNAL FEATURES

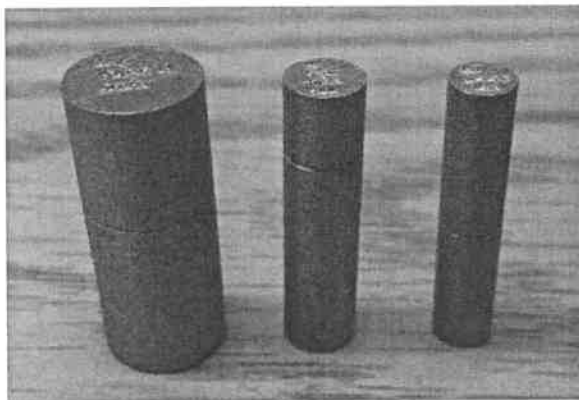
The parts were produced using laser-based PBF AM processes with a system (EOS M270) available at the National Institute of Standards

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and Technology (NIST). Nickel-based super alloy (Inconel 625) powder (between 15 μm and 60 μm in particle size as measured by standard sieves) was used. The laser spot size is approximately 100 μm , and the default machine parameter settings were used for the material. Three samples were designed with interior features incorporating different sizes and orientations of cubes and spheres, as shown in FIGURE 1. Un-melted powders are expected to be trapped in the voids. The outer diameters of the samples are 10 mm, 6 mm, and 5 mm, respectively.



(a)



(b)

FIGURE 1. Designs of the samples with different internal features (a) and picture of the samples after the build (b).

X-RAY CT INSPECTION

Metrological XCT

Metrological XCT measurements were obtained for the three samples using an XCT system (Nikon XT H 225 ST). One of the main advantages of metrological XCT is the use of calibrated voxel size. Typical XCT techniques

estimate voxel size based on magnification factor alone. However, there is potential for dimensional errors with this approach due to axis position errors, geometric alignment error of CT system hardware, and X-ray focal spot drift error. Further, image quality can be affected by physical factors such as beam hardening and the scattering of X-rays, which need to be either prevented by hardware filtering or compensated with post-processing corrections after CT reconstruction.

For the current measurement, a calibration of the voxel size and a beam hardening correction were performed. The voxel size calibration is achieved in a similar fashion to the guidelines from [7] by running a CT scan of a calibration object (FIGURE 2) with the identical scan settings to those used in measuring the test pieces. The calibration object is a hollow aluminum cylinder, which was measured with a coordinate measurement machine (CMM) to obtain reference dimensions. The XCT scan parameters are shown in TABLE 1. Slight differences between the effective voxel size calculated based on uncalibrated geometric magnification and the calibrated voxel size are noticed.

For CT measurements, the samples were mounted at an angle of 20° from the vertical axis to avoid cone-beam artifacts.

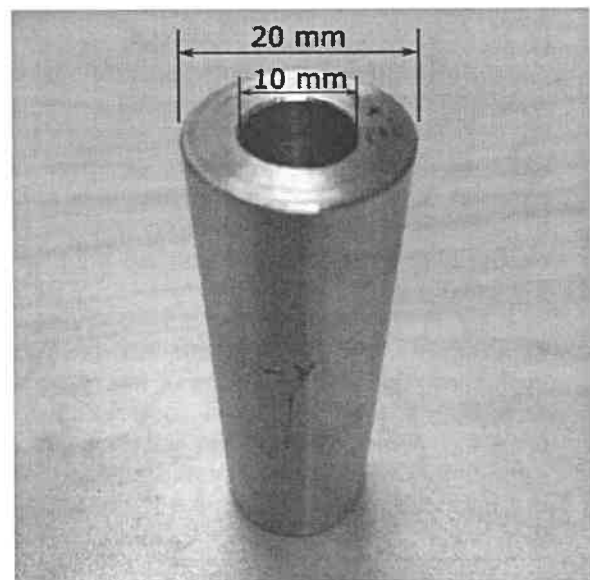


FIGURE 2. XCT calibration object

TABLE 1. XCT scan parameters

Sample	Large Cube	Small Cube	Sphere
Voltage (kV)	200	180	180
Current (μ A)	91	90	90
Power (W)	18.2	16.2	16.2
Filter Type and Thickness	Copper 3 mm	Copper 3 mm	Copper 3mm
Exposure Time (ms)	1000	1000	1000
Number of Projections	2880	2880	2880
Frame Per Projection	1	1	1
Detector Pixel Size (μ m)	200	200	200
Geometric Magnification	14.29	15.32	15.32
Magnification-based Voxel Size (μ m)	14.00	13.06	13.06
Calibrated Voxel Size (μ m)	14.05	13.08	13.08
Percent Difference (%)	0.36	0.15	0.15

Feasibility of Building Internal Features

Vertical interior slices at about the midsection of each sample are shown in FIGURE 3. High contrast of the solid parts was achieved, and the voids filled with powders can be easily distinguished from the solidified structure. The powder-trapping void looks darker due to porosity and the fairly coarse spatial resolution compared to the powder size.

In the sphere sample, the 200 μ m diameter spherical pore was not built. At the current XCT spatial resolution, no visible pore is found in the area. Both the spheres and the small cube experienced difficulties with producing accurate top surfaces. On the other hand, the large cube was built relatively well despite the larger overall dimensions. Small (100 μ m dia.) holes were designed and incorporated for the purpose of possibly getting the powders out, but they also did not appear to be built. Unintentional pores were not visible in the XCT images at the spatial resolution used, which confirms that the AM

processing parameters used were optimal to reduce porosity formation.

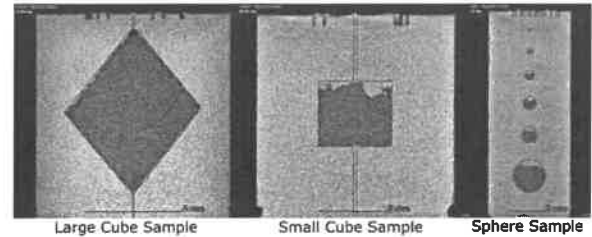


FIGURE 3. Results of metrological XCT scans and CAD overlaid.

Nominal to Actual Comparison

The metrological XCT images were directly compared to the CAD drawings as shown in FIGURE 4, 5, and 6. The XCT surface was registered to CAD via an iterative best-fit algorithm. The nominal geometry locations were subtracted from the actual position in the surfaces determined from XCT volumes. The deviations from the nominal geometry were as large as about $\pm 100 \mu$ m, and the locations with deviations larger than $\pm 50 \mu$ m are highlighted as red and magenta in the inner figures.

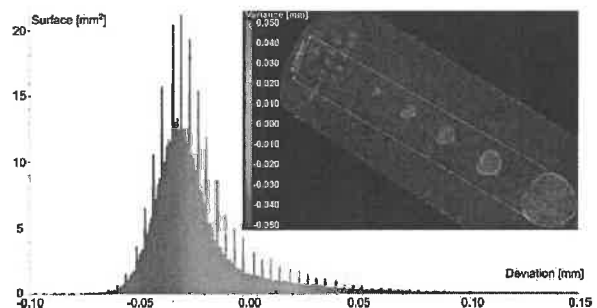


FIGURE 4. Part-to-CAD comparison showing the variance distribution for deviations of the CAD model for the sphere sample.

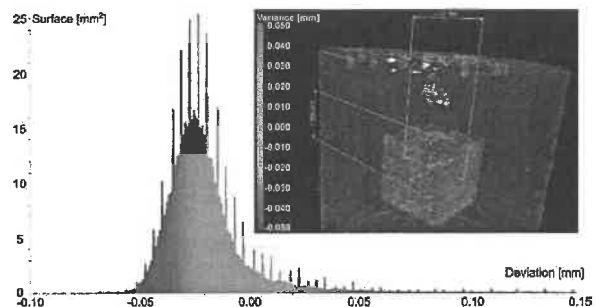


FIGURE 5. Part-to-CAD comparison showing the variance distribution for deviations of the CAD model for the small cube sample.

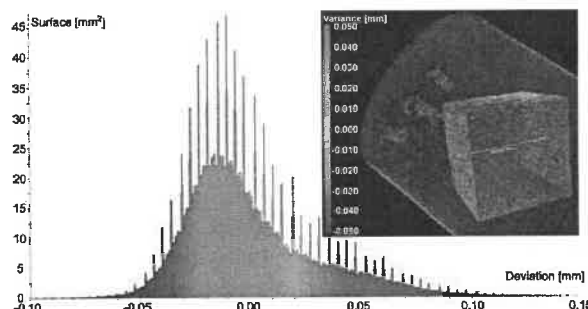


FIGURE 6. Part-to-CAD comparison showing the variance distribution for deviations of the CAD model for the large cube sample.

The nominal and actual volumes of the internal features are compared in TABLE 2. The difference between the nominal and actual volumes increased as the interior feature size decreased. The actual volumes were always smaller than the nominal volumes for the chosen designs due to inaccurate production of the top surfaces.

TABLE 2. Nominal and actual volumes of voids

	Nominal (mm ³)	Actual (mm ³)	Difference (%)
Large Cube	125	122.064	2.349
Small Cube	8	7.282	8.975
Sphere (2 mm dia.)	4.189	3.628	13.388
Sphere (1 mm dia.)	0.524	0.417	20.359
Sphere (0.8 mm dia.)	0.268	0.199	25.769
Sphere (0.6 mm dia.)	0.113	0.078	31.033
Sphere (0.4 mm dia.)	0.034	0.017	49.269

Improved Design

Based on the XCT images of the initial prototypes, an improved design is proposed to be built as an artifact for determining PoD, and an example design is shown in FIGURE 7. The design involves cubes of different sizes that are

in rotated orientations. The cubes in this orientation are expected to be built closer to the nominal designs. Subsequent XCT measurements are planned for the new design.

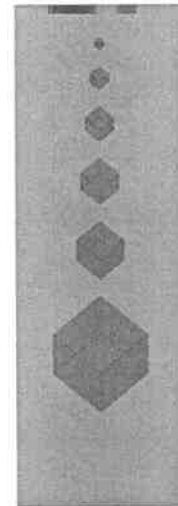


FIGURE 7. An improved design of test artifact

CONCLUSIONS

Samples incorporating internal features were built, and metrological XCT scans were obtained for the samples. The XCT scans were aligned with nominal CAD drawings for a direct comparison. Deviations up to ± 0.1 mm were detected between the nominal and measured dimensions of the AM-produced parts using XCT. Typical uncertainties of the CT measurements are in the order of $10 \mu\text{m}$, which is a factor of five smaller than the measured deviation. Therefore, the $\pm 50 \mu\text{m}$ -tolerances are predominantly related to the AM process rather than the measurement uncertainty.

XCT has the ability to generate geometric data for characterization of material structures (internal and external features) and detect manufacturing defects and dimensional deviations from CAD design. To study complex structures produced by the additive manufacturing process, XCT is becoming a viable option to extract component dimensions of inner or hidden structures in a non-destructive manner. The XCT measurements also provided insights on building and embedding internal features using metal PBF processes. The metrological XCT of the controlled specimens provides good base-line data for measuring internal features. The obtained results can ultimately be used to quantitatively determine detectability of internal features using XCT.

Future plans include obtaining additional XCT images from different XCT systems for a comparison. Once all XCT scans are completed, a destructive measurement will be performed.

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COMPUTED TOMOGRAPHY TO EVALUATE LARGE AREA PROJECTION MICRO-STEREO-LITHOGRAPHY (LAP μ SL)

Alex A. Dooraghi, Jefferson A. Cuadra, Julie A. Jackson, Bryan Moran,
Robert M. Panas
Lawrence Livermore National Laboratory (LLNL)
Livermore, CA, USA

INTRODUCTION

The Large Area Projection Micro-Stereo-Lithography (LAP μ SL) system has been developed at LLNL that can print at an unprecedented feature-size-to-part-size ratio (1). For instance, this system is capable of producing features of less than 10 μm over an area of 10 cm. LaP μ SL is integral to LLNL efforts to create metamaterials. However, before deploying systems, it is necessary to verify performance. Consequently, appropriate quality control procedures are essential in order to design bounds for system operation. Computed tomography (CT) provides a powerful tool to evaluate the structure of additively manufactured parts.

LAP μ SL was used to build the cylinder scaffold shown in figure 1 from 1,6-Hexanediol diacrylate [$\text{H}_2\text{C}=\text{CHCO}_2(\text{CH}_2)_3-$] $_2$. This structure will eventually be used for an energy storage device.

CT images of this structure were analyzed to assess strut thickness in the transverse and longitudinal direction. After varying the value of the linear attenuation coefficient to set a threshold for determining an optimum value for the segmentation of the struts, the average deviation of the CT imaged strut lengths from the ground truth is determined to be 1.6 μm with a standard deviation of 2.5 μm .

Considering the voxel size of the CT measurement is 3.22 μm , voxel size may be the dominant factor in limiting dimensional accuracy. More variation in strut size is observed in the transverse direction as oppose to the longitudinal direction as the part was built in the longitudinal direction.

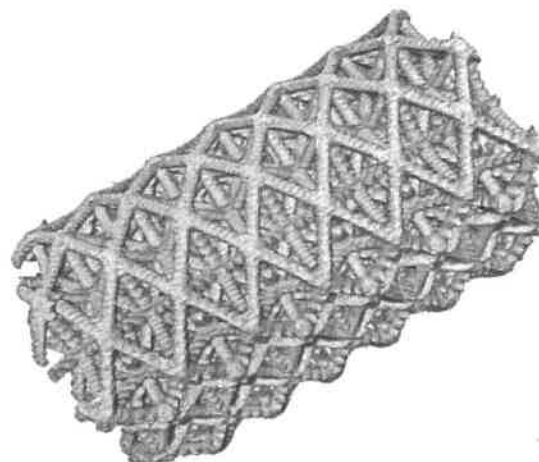


Figure 1. 3-Dimensional CT rendering of the cylindrical scaffold

METHODS

LAP μ SL system

LAP μ SL is an additive manufacturing technique that uses light and photocurable liquid to create highly complex, 3D structures (1). Like most AM systems, LaP μ SL creates structures "layer-by-layer". This process is unique in that it combines traditional stereo lithography (SLA), which creates layers by rastering a laser through photocurable liquid, with projection micro-stereolithography (P μ SL) which projects an entire layer at once (2). While traditional SLA, P μ SL, and other similar systems can produce 3D structures with features on the order of microns, the build area is often on the order of millimeters and large parts can take weeks to build. LAP μ SL combines these two techniques by utilizing a spatial light modulator (SLM) and galvo mirrors to scan multiple images over multiple centimeters.

Figure 2 shows a schematic of the LAP μ SL system. During the operating process, UV light is reflected off a digital micromirror device (DMD) and transmitted through a series of optics. As the image to be built transmits through the optical train, it hits the scanning optics (galvo mirrors) which directs the light through focusing

optics before hitting the build plane. As the light hits the build plane, it crosslinks the photocurable monomer, creating a 2D layer that is a small portion of the 3D part. This process continues, layer-by-layer, until the 3D part is complete.

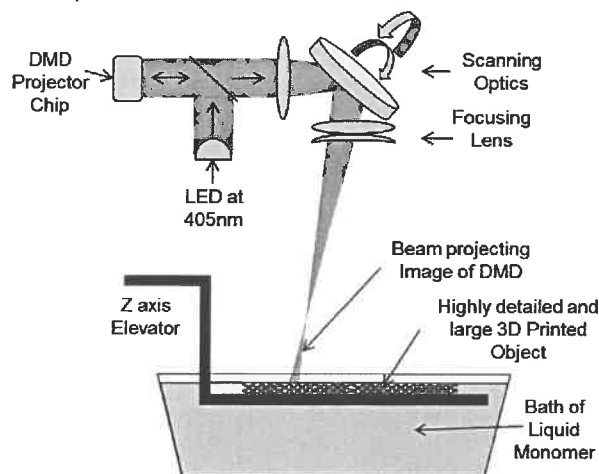


Figure 2. Schematic of the LAPμSL system.

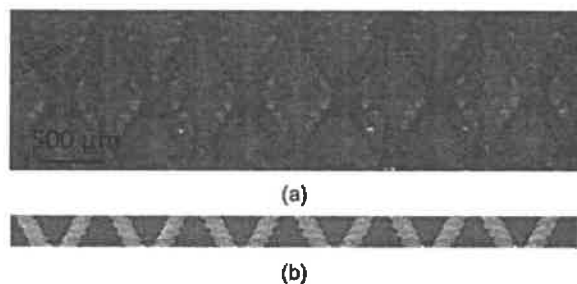


Figure 3. (a) Stereoscopic image of 24 struts used to determine ground truth thickness. (b) 12 of the 24 struts were identified in the CT image to determine an optimum threshold while the remaining 12 were used for validation.

Image acquisition

The object was imaged using the microCT 8.3.2 beamline at the Advanced Light Source (ALS) synchrotron facility located in Lawrence Berkeley National Laboratory using a 9 keV monochromatic source, and reconstructed using the filtered back projection algorithm implemented in Livermore Tomography Tools, LTT (3). The monochromatic radiation source provides the benefit of reducing artifacts due to the influence of additional complex error sources like beam hardening (4). The images were reconstructed into slices with $3.22\ \mu\text{m}$ voxels.

Threshold selection

Ground truth measurements for the strut thickness on a set of 24 struts located on the surface were determined with a Zeiss Discovery V12 stereo microscope by drawing line profiles of the struts on the stereoscopic images (figure 3a). 12 corresponding struts imaged with CT were segmented at various thresholds. A CT slice located at the center of the strut was selected for analysis (figure 3b). The average difference in length for 12 struts measured via stereoscopy and CT were plotted as a function of threshold. Linear regression was used to determine the threshold that yielded the smallest difference. This threshold was applied to 12 additional struts along the build to determine strut length, which were compared to ground truth measurements to determine accuracy and precision of threshold selection.

Transverse vs longitudinal strut thickness

With the optimal threshold selected, strut thicknesses in the longitudinal and transverse to build directions were compared. Histograms of the linear attenuation coefficient values in the transverse and longitudinal directions were compared to verify agreement of the linear attenuation coefficient values. A central slice of a set of rings in the transverse section was then compared to results from the longitudinal direction (figure 4).

RESULTS AND DISCUSSION

Threshold Selection

Figure 5 shows a plot of the average deviation from the ground truth as a function of threshold value. The threshold value that minimizes the differences is $0.059\ \text{mm}^{-1}$. This threshold was applied to 12 additional struts.

Average thickness measured via CT and stereoscopy is $131.0 \pm 2.5\ \mu\text{m}$ (standard deviation) and $132.6 \pm 2.5\ \mu\text{m}$, respectively. This corresponded to an average deviation of $1.6\ \mu\text{m}$ with a standard deviation of $2.6\ \mu\text{m}$. The voxel size of the CT measurement is $3.22\ \mu\text{m}$, which may be a limiting factor in the dimensional accuracy of the CT measurement.

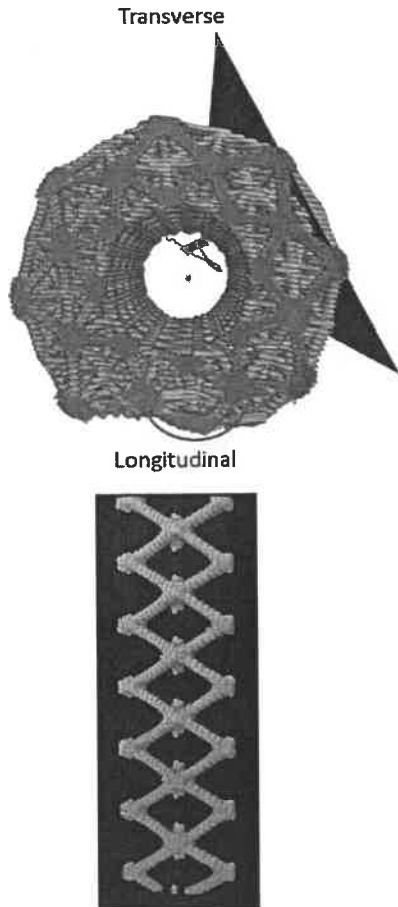


Figure 4. Transverse and longitudinal renderings of a set of struts. Red circle highlights the location of where the part was in contact with the AM system surface during the build.

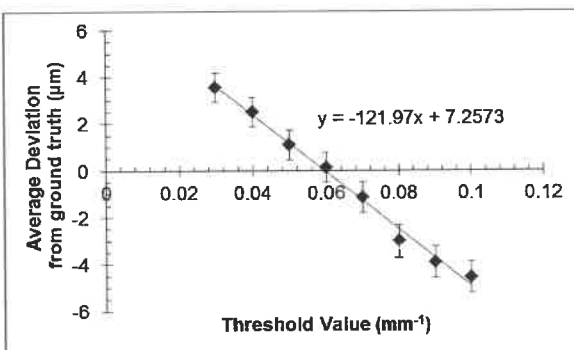


Figure 5. Plot of average deviation from ground truth as a function of threshold value.

Transverse vs. longitudinal strut thickness

Figure 6 shows good comparison of the linear attenuation values in the transverse and longitudinal directions, which is important in setting a single threshold value. Whereas the

average thickness in the longitudinal direction was measured to be 131.0 ± 2.5 , the average thickness in the transverse direction was measured to be $142 \pm 11 \mu\text{m}$. More uniform strut thickness is expected in the longitudinal direction as the part was built in the longitudinal direction.

Furthermore, as the part was built up on its side, the transverse direction is not as symmetric as the longitudinal direction. For instance, the initial build surface of the part in the LaP μ SL system is visible and highlighted in figure 4.

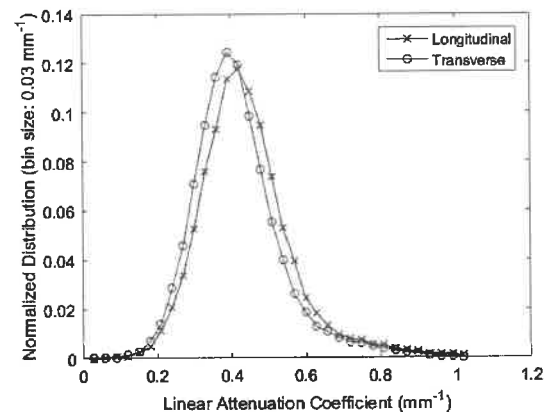


Figure 6. Histogram of the linear attenuation coefficients in the longitudinal and transverse directions.

CONCLUSION

LAP μ SL is in it's infancy at LLNL. While light intensity and distortion has been characterized, we do not have an adequate method to characterize the part built through this characterized light. It is possible to visually inspect parts manufactured by the LAP μ SL but this is limited to the exterior of the part. These parts are highly complex and they often have intricate features in their interior that offer valuable information. This information is only otherwise accessible through destructive methods such as destructive cutting called dicing. CT imaging of these structures allows for the non-destructive evaluation of the entire 3D structure. The characterization of the interior of the part provides valuable information on the process capabilities and part quality which can be extrapolated to other areas on the same part or other parts produced by the LAP μ SL system.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence

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ASSESSMENT OF DIMENSIONAL MEASUREMENT TOOLS TO MEASURE ADDITIVELY MANUFACTURED METALLIC PARTS

Stephen B. Brown, Wenjuan Sun, Michael B. McCarthy, and Peter Woolliams
Engineering Measurement
National Physical Laboratory
Teddington, Middlesex, UK

ABSTRACT

Additive Manufacturing (AM) has the capability to manufacture parts with more complex geometries and internal features than conventional subtractive manufacturing technologies. However, metallic parts produced by AM often exhibit a higher level of surface roughness than those produced by existing manufacturing processes; AM parts are also more likely to contain internal manufacturing defects, such as cracks and voids. These manufacturing differences pose challenges in the applicability of different dimensional measurement tools to provide accurate and precise dimensional measurements. This issue needs to be carefully addressed to ensure that parts made by AM, particularly those of complex "free-form" shape, are produced to within specified manufacturing tolerances.

In this paper we examine the ability of three different dimensional measurement technologies to provide accurate dimensional measurements on parts made by AM. The technologies used are traditional contact systems, such as tactile probing Cartesian coordinate measuring machines (CMMs), and two more modern non-contact technologies, namely optical scanning techniques and X-ray computed tomography (XCT). The latter two techniques are becoming more widely used in industry because of their respective abilities to provide rapid assessment of external and internal geometries.

An AM test standard, approximately (35 × 35 × 80) mm, designed by the National Physical Laboratory (NPL) and subsequently fabricated using Laser Powder Bed Fusion in aluminium alloy is described. Different geometries are considered in the design; these are included to firstly assess potential systematic errors from similar features and secondly to address issues such as beam hardening and scatter associated with XCT measurements. During measurement investigations, which are described, NPL's AM material test standard was mounted to a reference plate fitted with a number of precision ceramic tooling balls, enabling the dimensional

scaling errors of the different measurement tools to be compared.

Each of the three techniques: Cartesian CMM fitted with a tactile probe, optical scanning and XCT, were evaluated using the NPL AM material test standard and their dimensional measurement results compared. The results presented demonstrate that the confidence associated with the individual measuring techniques when measuring traditionally machined parts bearing smooth surfaces cannot be directly translated across to AM parts, where both the manufacturing material and the surface roughness form appear to influence the results. CMMs with tactile based probes, which are traditionally considered to provide the highest level of dimensional accuracy, were found to produce systematically different results on NPL's AM material test standard, depending on the selected diameter of the probe and other associated measurement settings, such as probing force.

Coordinate systems using optical sensors were found to be significantly affected by the level of surface roughness on the AM material test standard, making accurate determination of the position of the surface hard to achieve. The effect of translucency on the apparent diameter of a ceramic tooling ball also introduces a systematic error when defining its diameter.

The data from the test performed using XCT, provided the highest precision distance measurements, however, variations in values were influenced by machine settings, indicating that systematic measurement errors need to be carefully assessed.

The dimensional inconsistencies between the different techniques indicate that extreme care should be taken when making assumptions about a measurement system to be employed. The fact that some techniques provide high precision (a smaller spread of results), does not necessarily indicate that the measurements made are a true representation of the actual dimensions of the test part (*i.e.* poor accuracy).

There is a current lack of international standards covering the dimensional verification of XCT and

optical scanning techniques for making traceable dimensional measurements. There is therefore a need for robust best-practice guidance to be produced to enable end-users to obtain reliable dimensional measurements of parts manufactured by AM processes.

INTRODUCTION

Additive manufacturing, also often referred to as 3D printing, started its commercial life as stereo lithography as far back as 1987, where thin layers of ultraviolet light-sensitive liquid polymer were solidified using a laser [1]. Although the technology has been used for several decades, it is still in its infancy relative to other manufacturing processes [2]. Disciplines in which AM is being used include: aerospace, automotive, industry, lifestyle products, and medical.

The aerospace industry is generally where other industries look for initiatives and it is in that industry that the challenge over the last four decades has been shifting from getting airborne easily and safely to enhancing the cost and environmental efficiency of the flight. Aerospace has been looking increasingly towards employing AM to achieve this efficiency through reduction in mass, through the redesign of existing parts, and more efficient engines by incorporating AM parts which could not previously be manufactured by conventional machining methods. The same reasoning that has caused AM to be used in aerospace has led to its proliferation in the other areas mentioned above.

In any manufacturing process, where a part has been manufactured to defined design specifications, confidence that the part manufactured conforms to that design relies on the part being measured and these measurements being compared with the original design.

INSTRUMENTATION

In modern dimensional metrology, there are several techniques for dimensional measurement of engineered parts and those typically used, and discussed in this paper are: X-ray computed tomography, optical scanners, such as fringe projection, and tactile CMMs.

TACTILE CMM

Dimensional measurements on a tactile CMM are achieved by manipulating a sensor in a combination of translations and rotations in the x , y and z axes of a rigid system. In this paper, the system employed, see figure 1, was the Mitutoyo

Crystal Apex C 7106, with a measuring volume of $(705 \times 1005 \times 605)$ mm, the system is quoted by the manufacturer to have an MPE_E of $(1.7+0.3L/100) \mu\text{m}$, where L is the length measurement in mm.

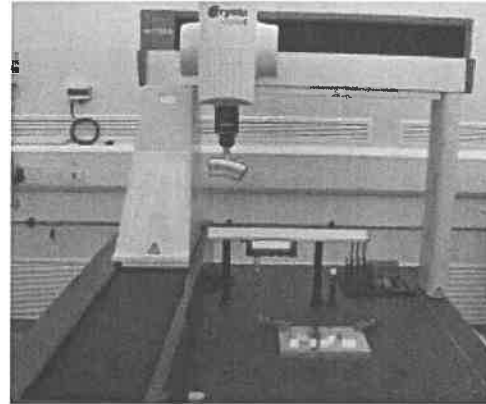


FIGURE 1. NPL's Mitutoyo CMM.

OPTICAL SYSTEMS

This section discusses two techniques that were used to capture data from the NPL material test standard. These techniques were, a line scanner attached to an articulated arm and fringe projection. Line scanners and fringe projection systems rely on projecting single or multiple lines onto an object and comparing this pattern as viewed from a known position, to the original projected pattern. A typical articulated arm can be seen in figure 2.

There are a multitude of optical 3D shape scanning measuring systems using different techniques [3], which claim a multitude of measurement uncertainties

Figure 3 and figure 4 shows a fringe pattern, projected onto a freeform surface, as viewed from a position perpendicular to the pattern and away from the line of sight of the scanner. The system used in this study was a FARO Edge ScanArm, with a high-definition Laser Line Probe HD head attached. According to the manufacturer's brochure, this system is quoted as having 'Accuracy of $\pm 25 \mu\text{m}$ ($\pm 0.001\text{in}$)'. Although measurements were also taken of NPL's material test standard, they have not been included in this report.



FIGURE 2. Articulated arm, FARO Edge ScanArm.



FIGURE 3. NPL's freeform standard, viewed with a fringe pattern projected.



FIGURE 4. NPL's freeform standard, viewed with single projected laser line.

X-RAY COMPUTED TOMOGRAPHY

The technique employs the X-ray absorption properties [4] of the material of an object being examined. A typical set up of a cone beam XCT system can be seen in figure 5, which illustrates the position of the X-ray source, the rotary stage and the detector [5].

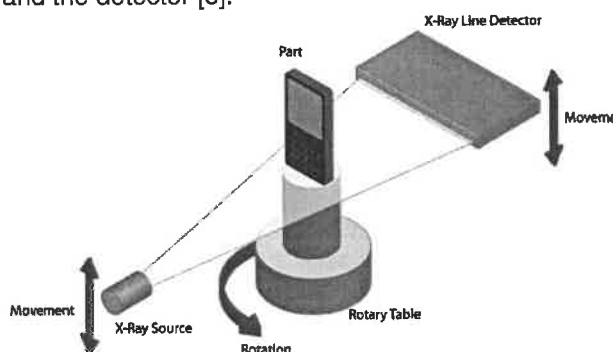


FIGURE 5. Typical cone beam XCT system setup.

X-rays are generated when high energy electrons are fired at a target material, where a transfer of energy occurs between the high energy ballistic electron and the material. Most of this energy is transferred into heat, where nuclear interactions take place the ballistic electrons may dislodge an

electron from the nuclear shell resulting in the eventual release of a characteristic X-ray photon [6]. Where these ballistic electron interact with the electron shell without the removal of a shell electron, energy is transferred into bremsstrahlung radiation [7].

In this study, the system used was a Nikon 225 kV XTH 225M, which exhibits both characteristic and bremsstrahlung radiation. The manufacturer states an absolute accuracy, in accordance with the VDI/VDE 2630, of $(9+L/50) \mu\text{m}$ where L is the length measurement in millimetres.

DESIGN CRITERIA FOR AN NPL MATERIAL TEST STANDARD

When designing a material test standard that would be used for the investigation of the different 3D measurement metrologies, consideration was given to the following aspects:

- The test standard demonstrates typical issues with AM manufacturing, for example, distortion in the part as it is built layer by layer.
- The material of the standard is AlSi10Mg, which is a common material used in AM.
- Inclusion of both external and internal features, which is different from conventional reference standards used in dimensional metrology. These conventional standards are reference artefacts such as gratings and step gauges, which do not have internal features.
- Both external and internal features are accessible by measurement techniques under investigation.
- The features have simple forms that can be characterized; cylinders, flats, and squares.
- Non-symmetrical arrangement is considered to address issues associated with the measurement technology.

A base plate was manufactured to which the AM part could be attached. The design included three high precision ceramic tooling balls. Ceramic tooling balls were chosen rather than the traditional steel balls, as their optical surfaces are conducive to efficient data capture. At the time of the measurements, shiny surfaces were known to be extremely difficult to measure using optical systems. The reference tooling balls provide reference scale.

Being precision spheres, the measurement of the surface and the determination of its centre, using

the applied least squares best fit routines, would result in low standard deviations. Values of both the diameters and centres were used in this evaluation to enable scale and surface determination of the separate techniques to be compared. An image of the NPL designed test sample attached to the base plate can be seen in figure 6.

These geometries were included in the design as internal and external form to allow the effects of beam hardening to be evaluated.

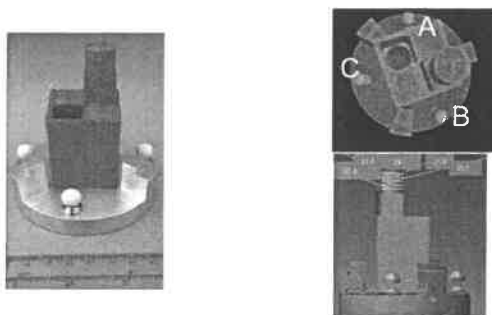


FIGURE 6. NPL test sample attached to base plate, with tooling ball and position of measured circles.

MEASUREMENTS

During the use of the three selected measurement systems used to measure the NPL material test standard, the material test standard remained attached to the base plate. Measurements were carried out at NPL under laboratory environment conditions that remained within: $20.0\text{ }^{\circ}\text{C} \pm 0.1\text{ }^{\circ}\text{C}$ and $50\% \pm 5\%$ relative humidity.

Application of the three different techniques being applied to the NPL material test standard and the reconstructed data are shown in figures 7, 8 and 9 respectively.

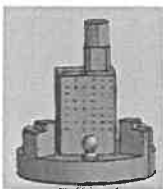


FIGURE 7. Tactile measurements reconstruction.



FIGURE 8. Optical measurements reconstruction.



FIGURE 9. XCT measurements reconstruction.

Tactile CMM

A tactile CMM was used to compare different measurements at different probing forces, of an AM part and one manufactured from aluminium. Comparison of diameters of circles, which were measured on the top cylinder using different probe diameters, were also completed.

Probe force

To evaluate the effect of different probing forces, a grid of 3×5 points was measured over two opposing faces of the NPL material test standard using probing forces of (0.05, 0.1, 0.25, 0.5, 1) N. Non-parallelism was calculated by averaging the distance between the paired points and comparing that to the individual distance between the paired points. The results are plotted in figures 10, 11 and 12 respectively.

Deviation from average width at probing force 1 N
AM Cube

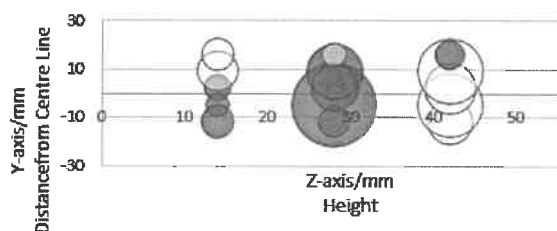


FIGURE 10. Deviation (shown by circle diameter of plot point, dark in-plane, clear out of plane) in width of AM cube at 1 N.

Deviation from average width at probing force 1 N
Machined block

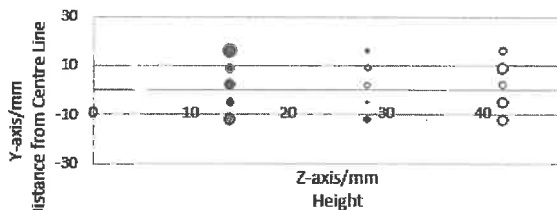


FIGURE 11. Deviation (shown by diameter of plot point, dark in-plane, clear out of plane) in width of Aluminium cube at 1 N.

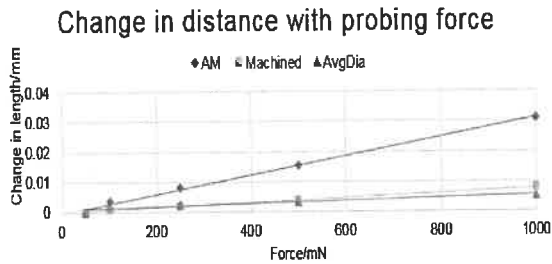


FIGURE 12. Change in distance with different probing forces.

Probe size

Measurements were made on the cylinder of the NPL test sample at a height of (18.5, 21, 23.5, 26, 28.5) mm from the datum plane. The datum plane is defined by a least squares best fit plane using the points measured on the top interface plane separating the internal and external cylinder and cube features. There were approximately 5187, 5074 and 4724 points taken using the (3, 4 and 5) mm diameter probes respectively. A plot of the results can be seen in figure 13.

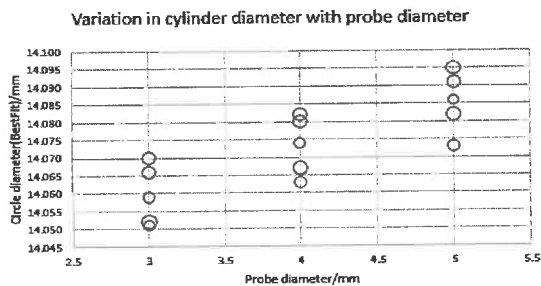


FIGURE 13. Probe size comparison (circle diameter indicates best fit standard deviation).

Tactile measurements

The tactile measurements used in the comparison to the optical and XCT measurements, were made using a 4 mm diameter ruby probe, the results are shown in table 1.

TABLE 1. Tactile CMM dimensional measurements.

Item	Results /mm	Profile results	
Dia A	9.991	Height /mm	Dia /mm
Dia B	9.991	18.5	14.070
Dia C	9.992	21.0	14.051

Item	Results /mm	Profile results	
Dist A-B	68.381	23.5	14.066
Dist A-C	50.769	26.0	14.052
Dist B-C	57.820	28.5	14.059

Optical measurement

Measurements were made of the NPL material test standard using a line scanner mounted on an articulated arm. The results are shown in table 2.

TABLE 2. Optical dimensional measurements.

Item	Results /mm	Profile results	
Dia A	9.912	Height /mm	Dia /mm
Dia B	9.803	18.5	13.854
Dia C	9.928	21.0	13.841
Dist A-B	68.444	23.5	13.839
Dist A-C	50.795	26.0	13.855
Dist B-C	57.845	28.5	13.870

XCT measurements

Images were captured using the NPL XCT system previously described and reconstructed using the manufacturer's supplied software 3D CT Pro to produce a voxel dataset. Analysis of the data set was completed using VG Studio Max 2.2. The results are shown in table 3.

TABLE 3. XCT dimensional measurements.

Item	Results /mm	Profile results	
Dia A	9.985	Height /mm	Dia /mm
Dia B	9.985	18.5	13.895
Dia C	9.985	21.0	13.896
Dist A-B	68.367	23.5	13.893
Dist A-C	50.756	26.0	13.894
Dist B-C	57.812	28.5	13.894

DIMENSIONAL MEASUREMENT SUMMARY

Comparison between the data from the CMM, XCT, and the optical technique, gives us an indication that not all measurements systems perform in the same manner when required to measure, a relatively rough AM part. See table 4.

TABLE 4. Summary of dimensional results in mm.

Height	CMM		Optical Dia		XCT Dia	
	Dia	Std Dev	Std Dev	CMM-Optical	Std Dev	CMM-XCT
18.5	14.070	0.037	0.030	0.216	0.012	0.175
21.0	14.051	0.036	0.029	0.210	0.013	0.155
23.5	14.066	0.043	0.030	0.227	0.012	0.173
26.0	14.052	0.040	0.035	0.197	0.013	0.158
28.5	14.059	0.034	0.034	0.189	0.013	0.165

The data from table 4 also indicates that accuracy and repeatability should not be confused and that a good repeatability does not imply a good accuracy. This paper also highlights the need to ensure that when measurements are being completed on a tactile CMM of an AM part, of relative roughness, similar measurement setups should be followed to ensure that systematic errors due to issues such as probe diameter and force are minimised.

CONCLUSION

Depending on the metrology system being used to capture the measurement data and the construction of the part being measured, systems can behave differently. Operators should not only rely on what the system is capable of achieving, but take into account the interaction of the system being used and the surface of the part being measured. As tactile, optical and XCT systems use different data capturing techniques, a systematic difference in dimensional measurements may exist that will invalidate the chain of traceability.

Acknowledgements

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INVESTIGATING THE CAPABILITY OF MICROFOCUS X-RAY COMPUTED TOMOGRAPHY FOR AREAL SURFACE ANALYSIS OF ADDITIVELY MANUFACTURED PARTS

Andrew Townsend¹, Liam Blunt¹, and Paul Bills¹

¹EPSRC Centre for Innovative Manufacturing in Advanced Metrology
School of Computing and Engineering
University of Huddersfield
Huddersfield, West Yorkshire, UK

INTRODUCTION

The ability to perform non-destructive areal surface analysis, for example of the internal surfaces of additively manufactured (AM) parts has potential advantages during product development and for production process control. This paper reports on the extraction of areal surface information from microfocus x-ray computed tomography (XCT) data. Using this novel technique a range of areal parameter values were generated from a surface section extracted from XCT scan data of an as-built (no post-processing) AISi10Mg additively manufactured part. This was then compared with the parameter values generated from a focus variation scan of the same surface section. The data comparison method involving normalisation of data format to allow analysis using industry-standard software, such as MountainsMap (Digital Surf, Besançon, France) or SurfStand (The Centre for Precision Technologies UoH) is demonstrated. Importing the extracted surfaces into these powerful software packages allows one-click data filtering per ISO 25178-3 [1] and the generation of a comprehensive suite of areal surface parameter values. These include feature and field parameters, amplitude, spatial, hybrid and functional parameters, as defined in ISO 25178-2 [2]. A method for characterising the capability of XCT for areal surface measurement is demonstrated by comparing results obtained from samples taken from a Rubert comparator test panel, with sample surface R_a values between 0.8 μm and 50 μm .

XCT AND FOCUS VARIATION AM SURFACE COMPARISON

A cube, 10 mm per side, was manufactured using selective laser melting (SLM) on a Renishaw AM250 using AISi10Mg powder. No post-processing, such as grit blasting, was performed after manufacture.

XCT Measurement

The cube was imaged using a Nikon XT H 225 microfocus CT. Nikon CT-Pro (Nikon metrology, Tring, UK) was used to perform reconstruction. Voxel size was 17 μm (x,y,z). Surface determination was performed in VGStudio MAX (Volume Graphics GmbH). Surface extraction (no simplification or downsampling, automatic surface determination) was performed in VGStudio MAX and the data was saved as an STL surface geometry (mesh) file. The surface was then imported into Meshlab (Visual Computing Lab ISTI-CNR), and area of interest (component upskin (top) surface) was aligned with the xyz coordinate system and then extracted and saved with a PLY file format.

Focus Variation

Focus variation (FV) instruments are commonly used to analyse the surface texture of additively manufactured parts and the FV results are used here as reference measurements. The upskin surface of the aluminium cube was measured using an Alcon G4 using a 10x objective lens. Vertical resolution was 0.2 μm and the lateral sampling distance was 2.3 μm . The data was saved as an STL file.

Areal Parameter Comparison

The XCT and FV STL surface sections were both imported into CloudCompare (version 2.6.3beta [GPL software] 2015). The areas were aligned using iterative closest point (ICP) and then both were cropped to give aligned, equal areas. No lateral or vertical scaling was performed during the alignment. Both areas were saved with PLY file formats. The XCT and FV PLY mesh files were levelled, projected onto a grid and converted to SDF (Surface Data Format) in Matlab (The MathWorks, Inc., Natick, Mass, USA. Release R2015b). Projected grid spacing was 2 μm (x and y), 1 nm vertical numerical resolution for both files.

A surface area of 5.6 mm x 5.8 mm, approximately 30% of the top surface area, was used for parameter generation, see Figure 1.

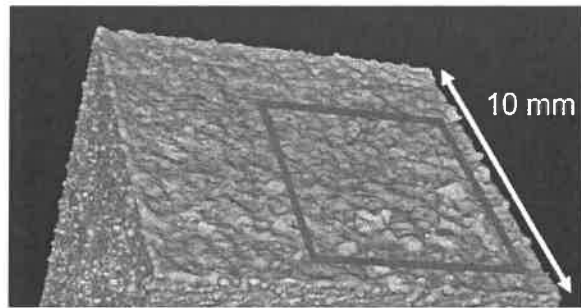


FIGURE 1. Top of AISi10Mg part after XCT reconstruction, showing cropped surface area.

The XCT and FV SDF files were opened in SurfStand (V6.0) software. Based on the surface (no structure of interest with a scale (wavelength) larger than 1 mm) the Gaussian L-filter nesting index was set to 5.0 mm and the S-filter nesting index was set to 0.02 mm, per ISO 25178-3:2012 tables 1 and 3. The FV and XCT false colour height maps, generated in SurfStand, are shown in Figure 2. The correlation between the surface topography of the two height maps can be seen clearly. Areal surface parameter data (per ISO 25178-2), computed in SurfStand from the FV and XCT data for these aligned and cropped areas, are compared in Table 1.

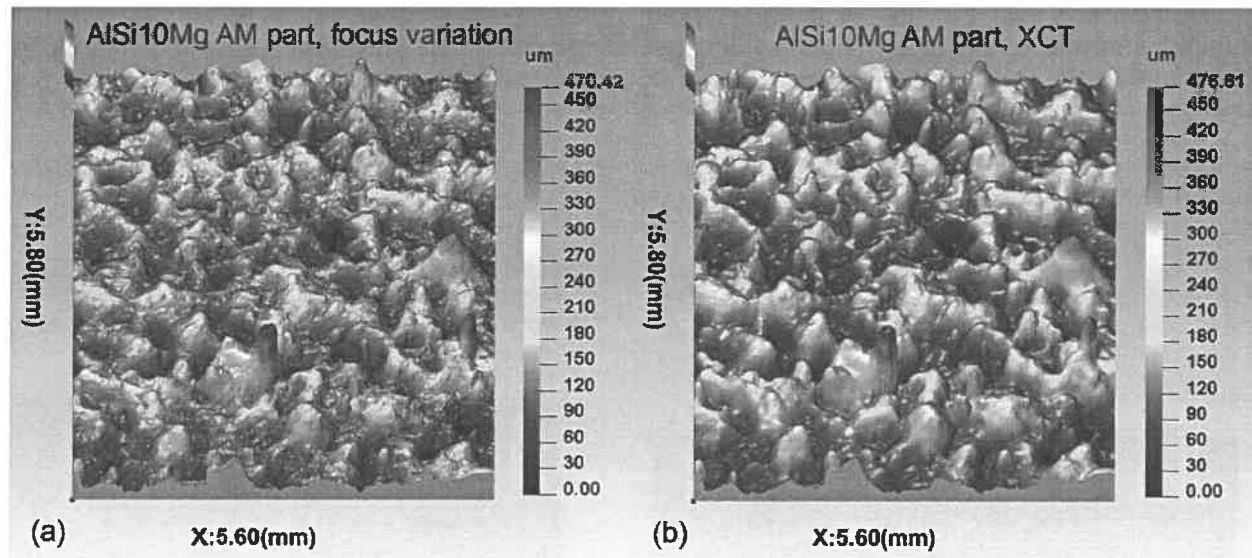


FIGURE 2. AISi10Mg part false colour height map (a) FV, (b) XCT.

TABLE 1. AISi10Mg part, FV and CT ISO 25178-2:2012 parameters.

Parameter	Description	FV	CT	Delta (% of FV)
Amplitude				
Sa	Arithmetic mean height	31.7 μm	40.7 μm	28.4%
Sq	Root mean square height	44.5 μm	53.2 μm	19.6%
Ssk	Skewness	1.72	1.13	-34.3%
Sku	Kurtosis	10.7	6.6	-38.3%
Sz	Maximum height	470 μm	477 μm	1.5%
Spacing				
Sal	Fastest decay autocorrelation length	0.27 mm	0.28 mm	3.7%
Hybrid				
Sdr	Developed interfacial area ratio	21.0%	21.4%	1.9%
Functional				
Smr2	Areal material ratio (dales)	90.8%	93.5%	3.0%

The surface parameters in Table 1 were chosen because they have all been shown to differentiate variations in AM build performance in response to changes in build parameters such as laser and electron beam spot size and power, build orientation and post-processing time [3]. The percentage variation between the XCT and focus variation measurements range between 1.5% for S_z (the sum of the maximum peak value and maximum pit height value) and -38% for S_{ku} (kurtosis). The kurtosis for the XCT measurement is 38% less than that of the focus variation instrument. This is understandable as kurtosis is an indication of “peakedness” of the surface and XCT resolution is considerably less than that of the focus variation instrument and so would tend not to resolve narrow, sharp peaks. S_a and S_q have been the most widely used areal parameters for AM surface measurement [3]. The values of S_a and S_q from the XCT were 28% and 20% greater than the focus variation measurements for this particular AM sample.

Mesh Distance Analysis

The distance (closest points) between the two aligned and cropped meshes was calculated and plotted, see Figure 3. The distance analysis map shows the good lateral scaling of the XCT. The distance distribution was also plotted, showing an approximately Gaussian distribution, and giving a standard deviation of 11 μm , see Figure 4.

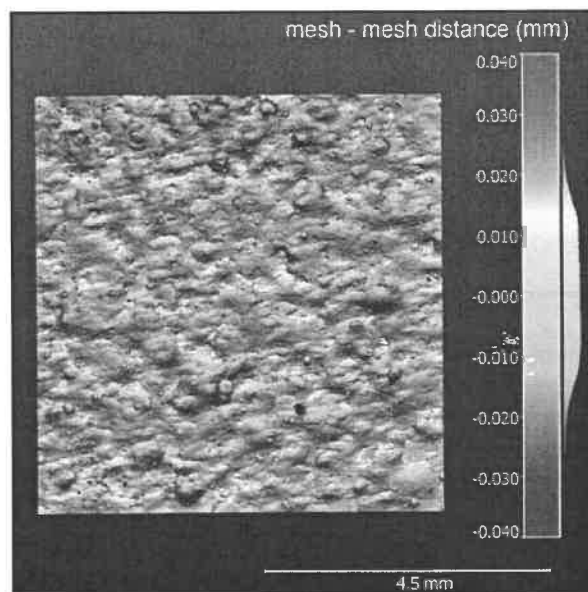


FIGURE 3. XCT to FV mesh difference map.

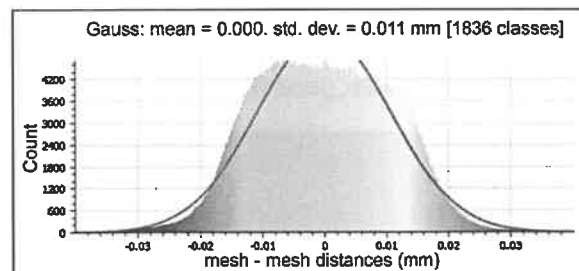


FIGURE 4. XCT mesh to FV mesh distance difference distribution.

XCT AND FOCUS VARIATION ROUGHNESS PLATE COMPARISON

The surfaces of powder bed fusion metal AM parts vary considerably with different manufacturing systems, powder configurations and build parameters. To give an indication of the limits of XCT to produce meaningful areal surface information a series of measurements were performed on test plates with roughness values encompassing those likely to be produced by metal powder bed fusion processes (nominal R_a 0.8 μm – 50 μm).

Rubert roughness comparison specimens

Seven plates, approximately 10 mm x 20 mm, were cut from a Rubert Microsurf 334 (casting) comparator test panel, see Figure 5.

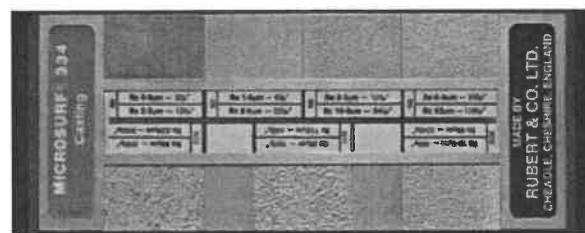


FIGURE 5. Rubert Microsurf 334 comparator test panel.

The casting panel was used as this surface most closely represents the powder bed fusion metal AM surface. No Rubert samples exist for AM surfaces at present.

Measurement and Analysis

XCT results were again compared to those obtained using the focus variation instrument. XCT voxel size for all plates was 12.9 μm (x,y,z). L-filter and S-filter nesting for indexes, based on plate R_a value, were generated using data from ISO 4287-1998 [4], ISO 4288-1998 [5] and ISO 25178-3:2012. The XCT and FV measured areas for each of the seven plates were aligned and

cropped following the same procedure used for the AISi10Mg AM sample. Nine square samples, with sample side lengths based on value of the L-filter nesting index, were extracted from the 0.8 μm – 6.3 μm R_a plates. Four samples were extracted from the 12.5 μm – 50 μm R_a plates (quantity limited by the plate sizes). The files were converted to SDF format, opened in SurfStand and the parameter set was generated. Table 2 shows the nominal R_a value together with the mean S_a value computed from the FV and XCT data for each of the seven plates.

TABLE 2. Rubert plate nominal R_a values, mean FV and XCT S_a values and percentage difference between mean XCT and FV values.

Nominal Rubert Plate R_a (μm)	Mean FV S_a (μm)	Mean XCT S_a (μm)	Difference between mean XCT and FV S_a (% of FV)
50	51.1	55.6	8.8 %
25	27.4	31.3	14.5 %
12.5	12.4	14.6	17.2 %
6.3	6.6	9.0	34.5 %
3.2	4.0	5.6	40.5 %
1.6	2.5	3.5	43.1 %
0.8	0.56	1.09	95 %

Figure 6a shows the four FV and corresponding XCT readings for the nominal 50 μm R_a plate. Figure 6b shows the nine FV and corresponding XCT readings for the nominal 0.8 μm R_a plate.

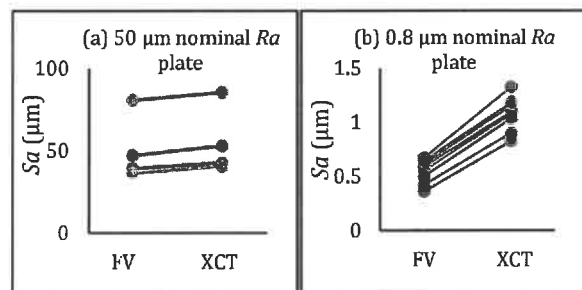


FIGURE 6. Comparison of FV and XCT results (a) 50 μm nominal R_a plate (b) 0.8 μm nominal R_a plate.

The lines on each chart are approximately parallel, illustrative of the correct FV to XCT mesh alignment. The gradients of the lines for the 0.8 μm R_a plate are greater, indicative of the larger percentage difference between the XCT and FV measurements than with the nominal 50 μm R_a plate. For each of the seven Rubert plates a

paired t-test was performed. The null hypothesis being that the difference between the mean S_a as measured on the XCT and on the FV instrument was zero. The 95% confidence level was then generated for the data from each of the seven plates. The mean S_a difference between FV and XCT readings, together with the 95% confidence level of the mean S_a difference were plotted for each of the seven Rubert plates. The values plotted are percentages of the mean FV reading for each plate, see Figure 7.

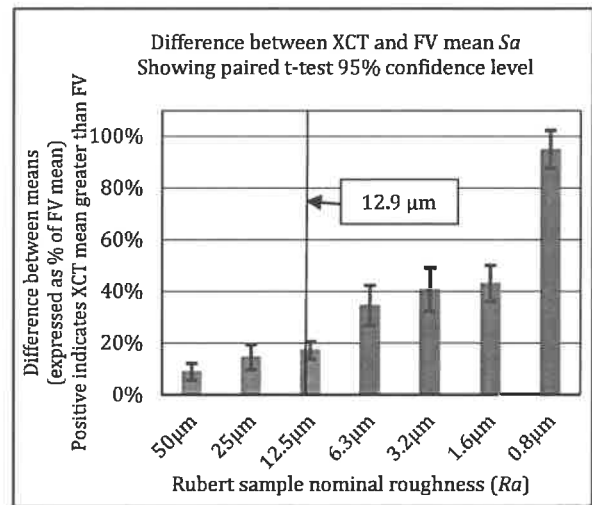


FIGURE 7. Chart of the mean S_a difference between FV and XCT for seven Rubert test plates.

The null hypothesis was rejected: for all seven plates there is greater than 95% probability the XCT measured roughness value is greater than the FV measured roughness value (none of the confidence interval bars cross the 0% line). The percentage difference between the XCT and FV measured roughnesses increases significantly as the absolute plate roughness value reduces (9% at nominal 50 μm R_a and 95% at nominal 0.8 μm R_a). There is a 2x step increase in percentage difference at an R_a value approximately equivalent to the 12.9 μm voxel size of the XCT. Mean differences between XCT and FV S_a measurements were 17% and 35% with sample roughness values (R_a) of 12.5 μm and 6.3 μm respectively. This significant increase in mean difference suggests an initial guideline that XCT areal surface measurements from surfaces with a reconstruction voxel size greater than the surface R_a or S_a should be avoided as errors increase significantly.

CONCLUSIONS

A novel first-step analysis technique has been developed to extract surface information from XCT data and configure this data to allow filtering and parameter generation, per ISO 25178-3 and ISO 25178-2 respectively, using commercially available software packages. Producing standard areal surface data from XCT would be particularly useful for the analysis of internal surfaces of additively manufactured parts, surfaces that up to now could only be analysed using destructive techniques. Initial characterisation of XCT surface measurement capability has been performed. These results show that, dependent upon voxel size and surface roughness, XCT is a viable method for areal surface analysis of AM components. Initial results show a marked decrease in accuracy when the voxel size exceeds the nominal surface R_a value. Additional applications of this technique beyond AM are expected.

FUTURE WORK

Currently there are no AM surface calibration or comparator test panels available and the results obtained for the single test of the AlSi10Mg AM surface produced a percentage difference for S_a values computed from XCT and FV (28.4%) higher than that of the approximately comparable Rubert casting plate, 25 μm nominal R_a , (14.5%), see Table 3.

TABLE 3. Rubert plate nominal R_a values, mean FV and XCT S_a values and percentage difference between mean XCT and FV values.

Test sample	FV S_a (μm)	XCT S_a (μm)	Voxel Size (μm)	Percentage difference
25 μm R_a Rubert plate	27.4	31.3	12.9	14.5 %
AlSi10Mg SLM	31.7	40.7	17	28.4 %

Future work will include measuring a selection of AM (and non-AM) surfaces to generate a more comprehensive understanding of XCT capability, including the relationship between voxel size and other factors such as surface determination, on measurement accuracy. Generation of a standard AM surface test plate will be investigated. Voxel size and resolution are dependent upon the position of the component being measured in the XCT chamber (in a cone-beam XCT machine a smaller voxel size will be

generated the closer the component is to the x-ray source). The position is dictated by the size of the component. The larger the component is the further away from the x-ray source the component needs to be to be imaged correctly and, subsequently, the larger the voxel size. These factors will be investigated and it is planned to characterise a variety of XCT machines for surface extraction capability.

ACKNOWLEDGEMENTS

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Dimensional Accuracy and Machine Variability of Titanium Parts Manufactured using the EOS Direct Metal Laser Sintered (DMLS) Process

Wesley F. Mitchell¹, Edward W. Reutzel¹, Terri A. Merdes², and Derek C. Lang³

¹Center for Innovative Materials Processing through Direct Digital Deposition

²Manufacturing Systems Division

³Guidance and Control Technologies Division

Applied Research Lab at Pennsylvania State University
University Park, PA

INTRODUCTION

Additive Manufacturing (AM) of metallic parts has many advantages to traditional manufacturing processes. AM allows for additional design freedom, consolidation of assemblies, complex lightweighting, and shortened supply chain [1]. Consequently, there is a desire to begin using metal AM parts in production applications. In order to accomplish that goal, the AM parts must be qualified, which will often require assessment of the dimensional accuracy [2]. An important aspect of such an assessment includes investigation of dimensional variability from build-to-build within one AM machine and dimensional variability between multiple AM machines. Acceptable dimensional accuracy on one AM machine can be used to qualify the production process while acceptable dimensional accuracy across multiple machines will allow the process to be scaled for larger production volumes.

A significant goal of this current research is to quantify and compare the dimensional accuracy of AM parts manufactured in Ti-6Al-4V on two EOS Direct Metal Laser Sintered (DMLS) machines. The analysis includes an assessment of the dimensional accuracy; process tolerance interval; machine run chart; and regression modeling of dimensional accuracy as a function of nominal part size.

EXPERIMENTAL SETUP

Eight AM builds were analyzed across two machines: an EOSINT M 280 and an EOS M 290. The builds were designed with the same layout to keep error sources to a minimum (see FIGURE 1). Included on all builds were parts explicitly designated for assessment of various build characteristics, including dimensional accuracy. These so-called "witness coupons" (see FIGURE 2) were measured upon completion of each of the key manufacturing processes required to deliver

a part for final finishing or machining: AM build, hot isostatic pressing (HIP), and part removal via submerged wire electrical discharge machining (EDM). Data presented in all subsequent analyses were from final part measurements, after part removal.

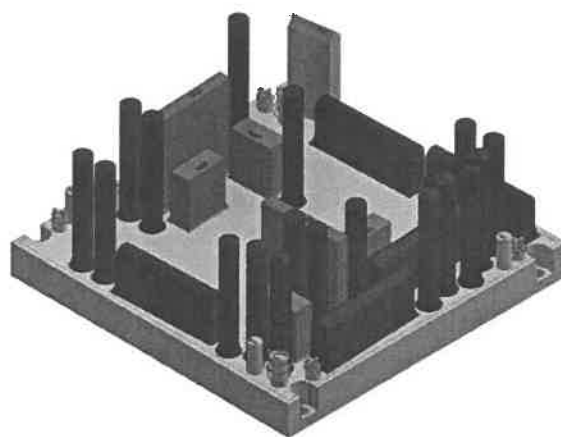


FIGURE 1. Part layout on AM build.

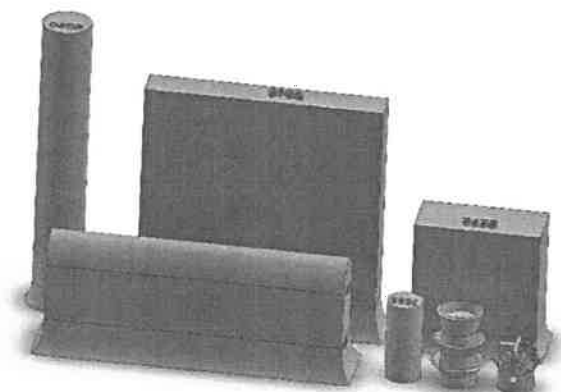


FIGURE 2. Witness coupons measured for dimensional analysis.

Additive Manufacturing Machines

The two AM machines used in this study were the Direct Metal Laser Sintering (DMLS) based EOSINT M 280 and EOS M 290. Four builds were completed on each machine.

Both EOS machine's galvanometer laser positioning scanners were calibrated during installation by EOS technicians. Also, a "fine-tuning" build was completed for each machine before the start of the production builds. The fine-tuning build is used to define the beam offset and scaling factors for a particular material parameter set (in this case, Ti-6Al-4V at 60 μm layer thickness). An analysis of the dimensional accuracy as a function of nominal part size was completed to evaluate the effectiveness of the fine-tuning calibration.

Measurement Procedure

Witness coupons were measured with calibrated calipers at each phase of the build process, as described above. The same technician measured all parts to eliminate user variability from influencing the results. The measurements were recorded and stored in a database for analysis. Only the final part measurements, after part removal, were analyzed to eliminate variability caused by the manufacturing processing steps.

RESULTS

The part size measurements were normalized by calculating the difference between nominal part size and measured size to obtain an accuracy value as shown below:

$$\text{Dimensional Accuracy} = (\text{Measured Size}) - (\text{Nominal Size})$$

The accuracy values were then analyzed to assess any systematic build-to-build or machine-to-machine variability, as well as to characterize trends with respect to nominal size (offset and scaling errors).

Dimensional Accuracy Run Chart

Dimensional data from all witness coupons on all eight builds were interrogated to assess the deviation from nominal as a function of each build (see FIGURE 3). In FIGURE 3, the boxes represent the distribution's interquartile range, the whiskers represent the upper and lower quartile, and the asterisks represent outliers. The median is shown as a horizontal line within the boxes. The mean is shown as a dot within the boxes and is connected between each build.

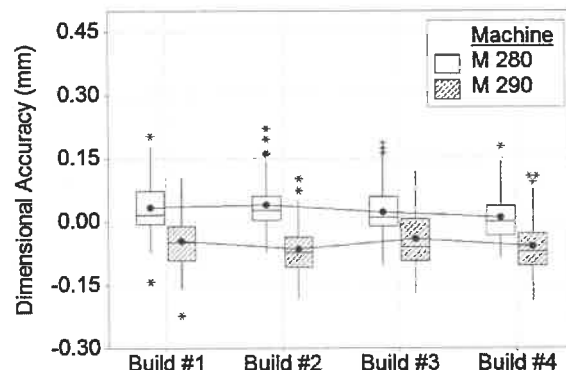


FIGURE 3. Box and whisker plot comparing dimensional accuracy across multiple AM builds and two AM machines.

An analysis of variance (ANOVA) produced results that showed the population means between each successive build, when restricted to each machine separately, were not significantly different at a 95% confidence level. Both the M 280 and M 290 machines produced consistent dimensional accuracy with respect to time. There was no statistically significant drift of the mean accuracy from build to build. However, as can be seen in FIGURE 3, there appears to be a difference between the means of all M 280 builds and all M 290 builds. An analysis of the two machine's dimensional accuracy distribution was completed to assess if the difference was statistically significant and is described below.

Machine-to-Machine Comparison

To assess the machine-to-machine variability, the dimensional accuracy data were separated into populations for each machine. The populations were then overlaid on a histogram (see FIGURE 4) for comparison.

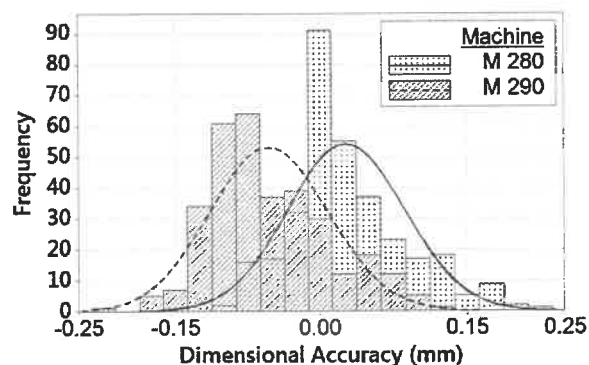


FIGURE 4. Histogram of dimensional accuracy differences between two AM machines.

The histogram shows that the two machines produced populations with similar variability but different means. The M 280 and M 290 data's standard deviation was 0.060 mm and 0.061 mm respectively. The means however were 0.027 mm and -0.053 mm respectively.

TABLE 1. Summary of dimensional accuracy descriptive statistics for two machine populations.

MACHINE	NUMBER OF SAMPLES	MEAN (mm)	STANDARD DEVIATION (mm)
M 280	326	0.027	0.060
M 290	326	-0.053	0.061

The two machine populations were compared using the *t*-test. To satisfy the prerequisite required to use the *t*-test, the two machine populations were tested to ensure they had equal variances. Using the two-sample F-test for equal variances, the null hypothesis was accepted (variances are equal) at a 95% confidence level. The corresponding *p*-value of 0.75 indicates there is no statistically significant difference between the variances of both machines since it is greater than the significance level of $\alpha=0.05$.

Since the population variances were shown to be equal, the two sample *t*-test could be executed. With a 95% confidence level, the *t*-test rejected the null hypothesis. Therefore, the means of each machine's dimensional accuracy results were different with statistical significance. The test statistic (*t*-value) was calculated to be 16.75 which is significantly greater than 1.96, the minimum value required to reject the null hypothesis at a 0.05 significance level. Also, the *p*-value was calculated to be less than 0.000, which is lower than the significance level of $\alpha=0.05$, further reinforcing that the means are different and the null hypothesis can be rejected.

TABLE 2. Results summary of the two-sample F-test for equal variances and two-sample *t*-test.

Test	Null Hypothesis (H_0)	Confidence Level	Accept/Reject H_0	<i>t</i> -value	<i>p</i> -value
F-test	Variances Equal	95%	Accept	-	0.75
<i>t</i> -test	Means Equal	95%	Reject	16.75	<0.000

Dimensional Accuracy as a function of Nominal Part Size

The "fine-tuning" builds (see FIGURE 5) that were completed on both EOS AM machines generated a beam offset, X scaling factor, and Y scaling factor. These three factors are used to account for the material shrinkage and melt pool geometry during the laser sintering process. The factors

are recognized as an approximation, since overall distortion depends on part size and geometry. To assess the effectiveness and accuracy of the fine-tuning build, the dimensional accuracy was plotted as a function of nominal part size (see FIGURE 6).

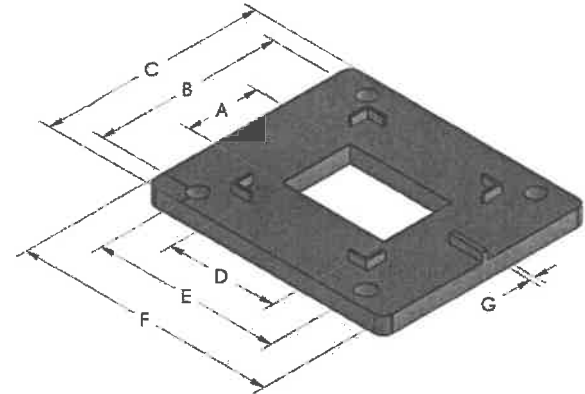


FIGURE 5. "Fine-tuning" build used to generate beam offset, X scaling, and Y scaling values.

Both linear and quadratic regression lines were fit to the data. Any systematic linear relationship between the dimensional accuracy and nominal part size can be partially attributed to inaccuracies in the beam offset and scaling factors calculated from the fine-tuning build. The regression analysis results actually showed that a quadratic line fit the data better than a linear relationship. The quadratic regression line had a better coefficient of determination in all instances (see TABLE 3).

Since the dimensional accuracy data did not show a linear relationship to nominal part size, the errors cannot be corrected with more rigorous fine-tuning build measurements and calculation of the beam offset and scaling values. A more robust technique must be implemented to correct for non-linear errors which may include items

such as a better galvanometer calibration technique [3]. Alternatively, EOS machines allow one to apply the material shrinkage factors on a part-to-part basis. Therefore, data gathered from actual parts on the first AM builds could be used to generate beam offset and scaling factors which would then be applied to each part independently. This technique could be performed iteratively on

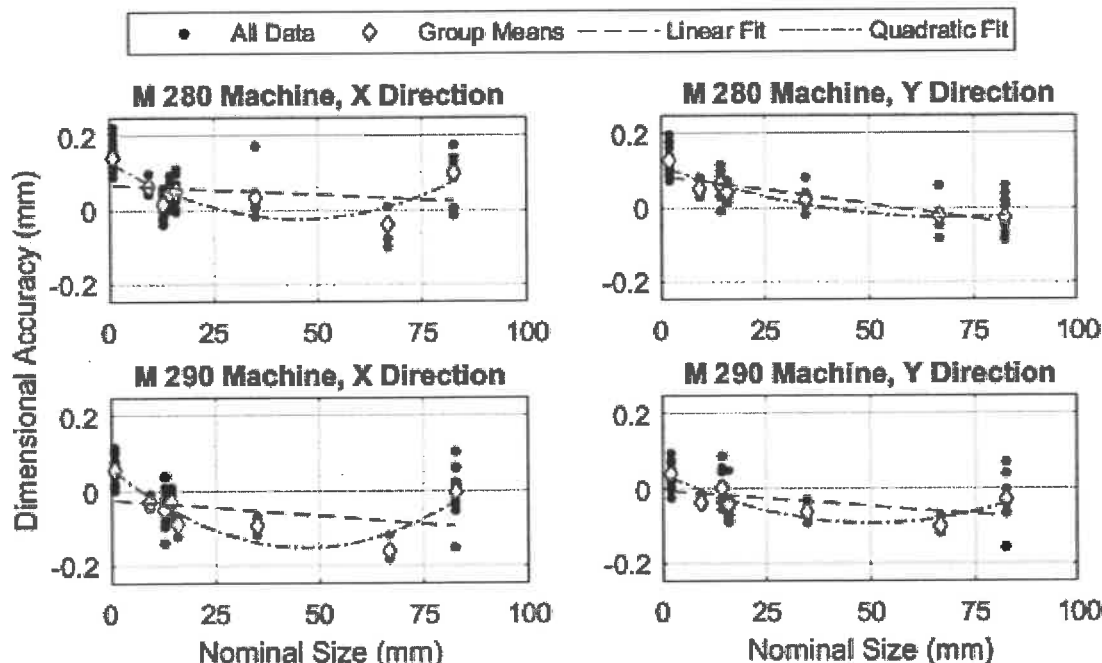


FIGURE 6. Dimensional accuracy plotted as a function of nominal part size with linear and quadratic regression models fitted to the data.

TABLE 3: Goodness of fit comparison between linear and quadratic linear regression models for the dimensional accuracy relationship to nominal part size.

Machine and Measurement Direction	R ² Value Linear Regression Model	R ² Value Quadratic Regression Model
M 280, X Direction	0.08	0.64
M 280, Y Direction	0.81	0.91
M 290, X Direction	0.15	0.79
M 290, Y Direction	0.34	0.78

each build to converge on beam offset and scaling parameters that produce parts as close as possible to the desired nominal part size.

CONCLUSIONS

The dimensional accuracy requirements of additively manufactured parts are driven by each individual application. Some applications can accept relatively loose dimensional control or the final parts undergo post-processing, and the results presented in this work would prove to offer adequate dimensional control. Other applications will require tighter dimensional control to meet the design intent. The data presented show there is room for improving the dimensional accuracy of AM parts for stringent dimensional accuracy applications.

Improving Machine-to-Machine Variation

The dimensional data collected and analyzed in this research show that the two EOS DMLS

machines evaluated produced Ti-6Al-4V witness coupons that had statistically different means. The measurements did however exhibit similar variances. These results suggest that the machines may be calibrated in a manner that would produce equal population means, and that each machine could then be used to produce parts that are dimensionally equivalent.

The machines did exhibit exceptional repeatability from build to build. There was little drift of the dimensional accuracy or variance for either machine. This is promising evidence to support the efficacy of using AM machines to manufacture parts in a production setting. For this sample of four builds, if the same build is setup and executed using a single machine, one can expect to produce the same part every time within the variability shown.

Improving Scale and Offset Errors

Machine accuracy with respect to nominal part size proved to exhibit the most interesting results. It was initially hypothesized that the factory galvanometer calibration would remove most of the part accuracy errors, and the additional "fine-tuning" build to calibrate associated beam offset and scaling factors would remove remaining errors. Any dimensional accuracy errors that remained, would be expected to follow a linear trend and thus could be attributed to inaccuracies in the X scaling, Y scaling, and beam offset calculation. What was observed, however, was a non-linear dimensional accuracy trend. These results are important because the non-linear errors cannot be compensated with additional refinement of the beam offset and scaling factors. A more in depth understanding of the nature of this variation and a more sophisticated procedure must be implemented to correct for these errors.

Potential corrections procedures may involve re-verification of the galvanometer accuracy to determine if non-linear errors are manifested at the machine level. If this is the case, than a simple galvanometer calibration may solve the issue [3]. An alternative theory is the material shrinkage is non-linear and dependent on part size and geometry. In this particular scenario, an all-encompassing, single set of beam offset, X scaling, and Y scaling factors will never be adequate to correct all the errors. Therefore, an iterative process would have to be implemented in which each part is measured after a build and new correction factors are input on a part-to-part basis for the next build.

FUTURE WORK

To address the issues uncovered in this experiment, it would be advantageous to continue collecting and analyzing data on the machine-to-machine variation. Additional data may prove useful in understanding the root cause of these dimensional accuracy differences, a necessary input to devising procedures which would improve the results. The work could build upon existing efforts to create a standardized test artifact [4] by using said artifact for calibration and verifying the results with multiple "production" builds across multiple machines.

It is also important to continue investigating the non-linear dimensional accuracy errors witnessed in the data. An independent verification, and re-calibration if necessary, of the galvanometer accuracy should be completed and

followed with additional AM builds for part dimensional accuracy verification. If the galvanometer accuracy is shown to not be the root cause, a procedure should be developed to implement beam offset and scaling factors on a part-to-part basis.

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CHARACTERIZATION OF ADDITIVE MANUFACTURING MATERIALS USING ENERGY DISPERSIVE SPECTROSCOPY

Lauren F. Elder, Ann S. Choi, David M. Wieliczka, Joseph A. Crow, Brandon M. Cox, Ronald D. Koch, and Shawn E. Van Slyke
Analytical Sciences
Honeywell
Kansas City, MO, United States

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INTRODUCTION

Understanding the morphology and elemental composition of raw material for additive manufacturing is critical to understanding the physical properties of the final product.

In 2014, Honeywell purchased an Aspex Explorer scanning electron microscope (SEM) to test additive manufacturing raw material samples at the Kansas City National Security Campus (KCNSC). The Aspex Explorer is an SEM that is specially designed for particle analysis.

The initial phase of the study examined the ideal operating conditions for the instrument allowing for the collection of accurate, repeatable results in the least amount of time. With a deeper understanding of these operating conditions a study was begun using more than 300 different stainless steel samples from various stages of an additive manufacturing recycling process study. The goal for the Aspex analysis of these samples was to use the amount of data gathered to gain a better understanding of the energy dispersive spectroscopy (EDS) detector on the instrument in relation to the spherical particles that were being analyzed.

This EDS analysis allowed us to garner more information on the proper detector settings in order to better characterize additive manufacturing particles using EDS. From this study we were also able to identify the minimum amount and types of data needed to relate raw material characteristics to bulk properties.

OVERVIEW OF SEM PARTICLE ANALYSIS

Standard SEM Analysis

At the KCNSC, particle analysis by SEM is a technique that has been used for 35+ years. However, until a couple of years ago, this process was very time consuming and difficult.

The standard SEM (in this case a Zeiss Leo 1455) analyzes particles using backscatter images analysis. This means that the software takes a backscatter image and analyzes the size and shape of the particles based on this image. Due to this, reported particle size and morphology can be influenced by image brightness and pixel size (magnification).

Aspex Explorer Analysis

The Aspex Explorer gains significant time on the Leo 1455 by using backscatter intensity analysis rather than backscatter image analysis. This time savings is shown in Table 1.

TABLE 1. Time savings in hours of the Aspex Explorer particle analysis vs. standard particle analysis on the Leo 1455 SEM.

	In hours			
	Instrument	Data	Total	
Leo 1455	8	7	15	
Aspex	1.5	1	2.5	
	Time Savings		12.5	/sample

Once the backscatter intensity threshold has been set, and the area of interest chosen, the software breaks the area up into fields of view. Each of these fields of view is broken up into a grid and the beam searches each grid intersection for anything that falls above the set intensity threshold. Anything over this intensity threshold is counted as a particle.

Particles are measured using an eight chord raster from the center of the particles to measure diameters and other morphology information. Figure 1 shows this process.

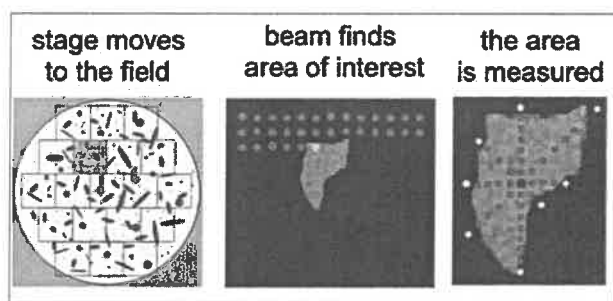


FIGURE 1. Image showing the process that the Aspex follows to identify and measure particles [1].

EDS ANALYSIS ON ADDITIVE MANUFACTURING PARTICLES

The final piece of particle analysis lies in the compositional analysis of the individual particles. Compositional analysis is done by energy dispersive spectroscopy (EDS).

EDS is a technique that uses x-rays emitted when the beam electrons eject electrons from the inner shell electrons of the specimen as shown in Figure 2. These x-rays are called characteristic x-rays and each element emits specific energy x-rays making identification of elements possible.

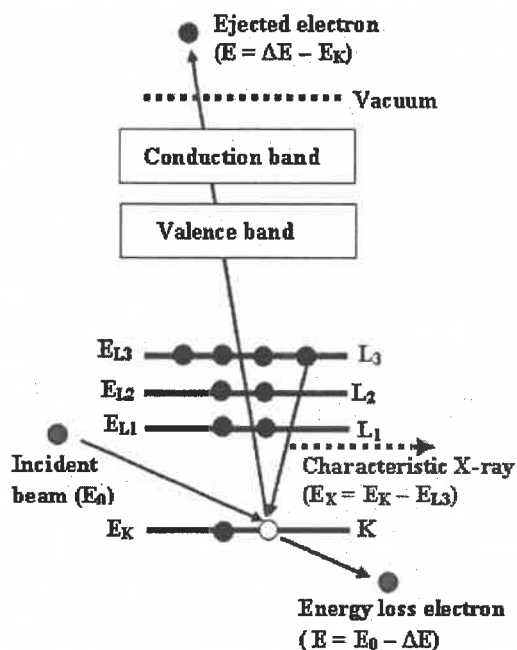


FIGURE 2. Image shows process for creating characteristic x-rays. High energy incident

electron (E_0). The energy loss (E) is transferred to the electron that is ejected. The space vacated by the ejected electron is filled by an electron from an outer shell. Extra energy is emitted as x-rays characteristic to the element that it came from [2].

EDS assumes that the x-rays are coming off of a flat infinite sample when it identifies elements and creates a semi-quant analysis which gives a rough estimation of the atomic percentage of the elements in the material. This assumption does create issues when measuring small spherical additive manufacturing particles. One of the goals of the study was to understand how these small spherical particles affect our EDS results.

STUDY OF EDS ANALYSIS OF ADDITIVE MANUFACTURING MATERIALS

Overview

Samples used in this study were taken from an additive manufacturing study on the recycling of raw materials. The goal of the recycling study was to learn more about how the raw material changes over time as a result of reuse. All samples were 316L stainless steel from various stages of reuse in the additive manufacturing process.

The samples were analyzed using the automated feature analysis (AFA) software that is part of the Aspex package. This AFA software enables users to program data collection runs for multiple samples.

The amount of samples analyzed produced a large amount of data allowing for thorough analysis of EDS results. EDS spectra from the Aspex were compared to spectra created by simulation software, DTSA-II, written by the National Institute of Standards and Technology. The DTSA-II software lets users create synthetic EDS spectra for spherical particles of any material using a Monte Carlo simulation.

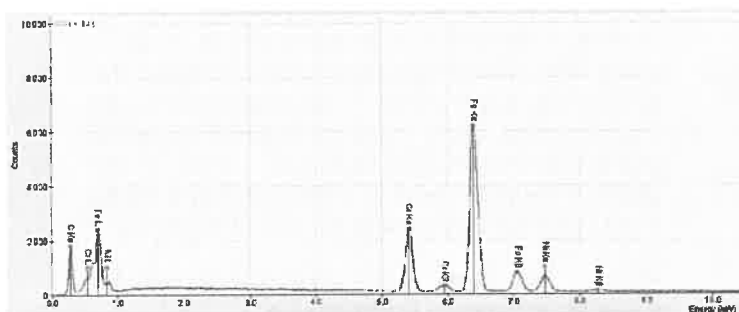
The second part of the study used the data collected to analyze how much of the material needed to be analyzed in the Aspex to be able to accurately understand the bulk material. This also led us to some discoveries about 'false' particles (i.e. two particles that the instruments mistakenly identified as one).

Results

EDS Analysis

It is not completely understood how spherical and irregularly shaped particles affect the EDS spectra on the Aspex Explorer. To gain a better understanding on how spherical particles affect the EDS results on the Aspex, the Desktop Spectrum Analyzer II (DTSA-II) software package was used to create synthetic spectrum to compare to the EDS spectra collected from the

The Aspex Explorer produces the EDS spectra and semi-quantitative elemental compositions for each particle that it analyzes. Figure 5 shows



Aspex. Figure 3 shows an example of what this simulated spectrum looks like for a stainless steel sample on a carbon substrate.

FIGURE 3. Simulated spectrum of stainless steel on a carbon substrate created by DTSA-II software.

DTSA-II factors in the sample morphology, instrument settings and detector type as it simulates EDS spectra. DTSA-II offers Monte Carlo and analytical simulations and since our samples have spherical geometries, the Monte Carlo simulation was chosen to generate the spectra. Figure 4 shows this Monte Carlo simulation for the iron in the stainless steel and the carbon substrate.

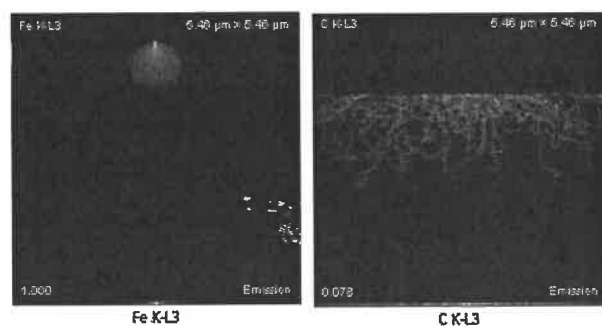
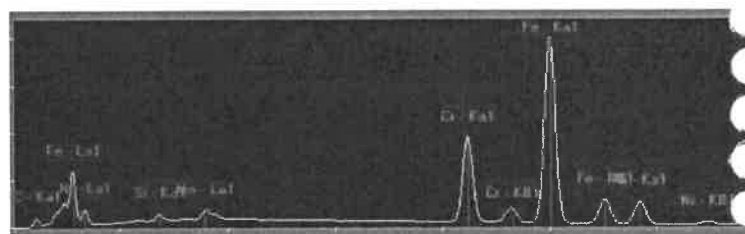


FIGURE 4. Monte Carlo simulation results showing the path of x-rays for a stainless steel particle sitting on a carbon substrate.



what this spectrum and semi-quant results look like.

FIGURE 5. Image showing stainless steel spectrum generated by the Aspex.

The differences between the software for the Aspex and DTSA-II make it unreasonable to directly compare the experimental and simulated EDS spectra. Instead, we collected the quantitative elemental composition from each method and observed how they compare to each other. 316L stainless steel particles with known material compositions were used for this comparison study. We compared the quantified elemental compositions for spherical particles with the simulated compositions from DTSA-II using the "Monte Carlo model of a sphere on a bulk, homogenous substrate" simulation. This allowed us to then analyze the irregularly shaped particles on the Aspex to observe how they differ from the perfectly spherical particles of the simulation. The comparison between the experimental EDS spectra from the Aspex and synthetic spectra simulated by DTSA-II provided a better understanding of how particle morphology affects the accuracy of the EDS results on the Aspex Explorer.

Number of Particles Used in Analysis

In the beginning of analyzing additive manufacturing raw material, it was decided to measure 2000 particles for each sample, a number decided on by joint decision between the analyst and the originator.

Further studies into the accuracy of morphology and EDS measurements over varying number of particles showed that the distribution of diameter, aspect ratio, roundness, and compositional data does not change based on number of particles after 2000. Therefore it is not necessary to gather

data on more particles before assuming the morphology and composition of the bulk sample.

Morphology Analysis and 'False' Positives

One of the issues that was brought up in the beginning of analyzing particles using AFA was the software mistakenly identifying two particles as one due to the fact that they were sitting close together as shown in Figure 5. Originators of the samples were concerned that this data may skew the morphology results.

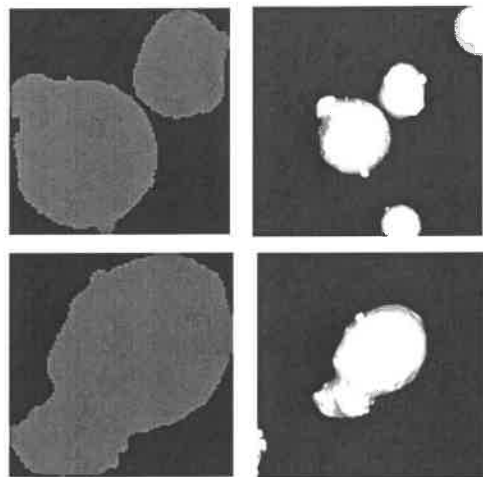


FIGURE 5. Top left image shows backscatter image of two particles sitting side by side. Top right image shows the representation that the software uses to mask the particles for measurement. Bottom two images show the equivalent image for actual merged particles.

Upon investigation it was discovered that these false positives stood out on plots that included roundness. Since 1.0 is a perfectly round particle and anything less than 1.0 is a less than round particle, these false positives stood out as having roundness greater than 1.0. An example plot of

roundness vs. average diameter is shown in Figure 6.

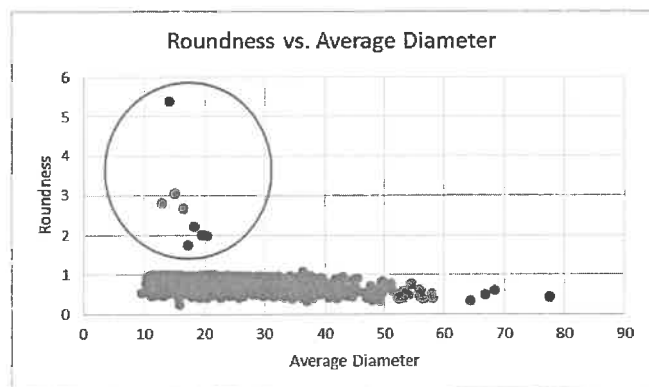
FIGURE 6. Plot of Roundness vs. Average Diameter showing outliers classified as false positives (circled).

Future Work

For future work, we would like to continue to get results from the comparison of spectrum between the actual EDS results and the simulated results that we get from the DTSA-II Monte Carlo simulation. This will allow us to more closely quantify how closely the stainless steel raw material meets the specification. We would also like to expand this study to include more materials such as 304L stainless steel, aluminum, and titanium powders.

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A HOLISTIC APPROACH TO METALS PROCESSED THROUGH ELECTRON BEAM MELTING

Michael M. Kirka¹, Ryan R. Dehoff¹, Yousub Lee¹, Alfred Okello¹ and R. B. Dinwiddie¹

**¹Manufacturing Demonstration Facility
Oak Ridge National Laboratory
Knoxville, Tennessee, USA**

ABSTRACT

Additive manufacturing (AM) represents a significant evolution in the method by which industrially relevant components can be designed and fabricated in manners not possible by traditional techniques. While there is much interest in the final performance of AM fabricated components, a holistic view of AM is necessary to achieve a successful outcome. This holistic approach concerns all aspects from the feedstock material through the final performance of the component. To be discussed are the efforts currently underway to develop the necessary framework for linking the feedstock material to the final performance of the fabricated component utilizing the electron beam melting (EBM) process. Specifically, the microstructure-property relationships of nickel-base superalloys and titanium alloys are considered within the context of their traditionally processed counterparts. Further the applicability of in-situ process monitoring and defect detection is discussed within the context of the EBM process and relation to providing a means to rapid certification and qualification of AM components.

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